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SPATIAL REUSE THROUGH DYNAMIC POWER AND ROUTING CONTROL IN COMMON-CHANNEL RANDOM-ACCCESS PACKET RADIO NETWORKS

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Topologies of common-channel packet radio networks (PRNETs) are difficult to optimize because some of the links between multiple pairs of packet radio units are not independent. Previous analysis has shown that designing the topology to provide spatial reuse of the common-channel will improve the network throughput and delay performance in general. Unfortunately, the complexity of the link interactions has impeded the design of protocols that can be implemented in operational networks. This dissertation discusses how to optimize the topologies of common-channel random-access PRNETs through dynamic power control at the link layer and routing at the network layer.

Methods of implementing dynamic power control at the link layer on an individual packet-by-packet transmission basis are presented. These methods should be implementable at the link layer of any packet radio with dynamic per-packet power control capability. (JES)

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A new routing protocol, called Least Interference Routing (LIR), is defined which is designed specifically to operate in common-channel random-access PRNETs. The goal of LIR is to minimize the destructive interference caused along each route within the network, thus improving the spatial reuse of the common-channel. The LIR protocol calculates the potential destructive interference along each link, creates the network routing tables that minimize the potential destructive interference along an entire route, and specifies the per-packet transmission power. The implementation flexibility of each of these operations allows LIR to be implemented in a variety of radios and radio networks.

Myopic one-hop and network multiple-hop simulations indicate that dynamic power control and/or LIR improve end-to-end PRNET performance over no power control or other routing strategies, such as minimum hop routing.

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SPATIAL REUSE THROUGH DYNAMIC POWER AND ROUTING CONTROL IN COMMON-CHANNEL RANDOM-ACCESS PACKET RADIO NETWORKS

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Topologies of common-channel packet radio networks (PRNETs) are difficult to optimize because some of the links between multiple pairs of packet radio units are not independent. Previous analysis has shown that designing the topology to provide spatial reuse of the common-channel will improve the network throughput and delay performance in general. Unfortunately, the complexity of the link interactions has impeded the design of protocols that can be implemented in operational networks. This dissertation discusses how to optimize the topologies of common-channel random-access PRNETs through dynamic power control at the link layer and routing at the network layer.

Methods of implementing dynamic power control at the link layer on an individual packet-by-packet transmission basis are presented. These methods should be implementable at the link layer of any packet radio with dynamic per-packet power control capability.

A new routing protocol, called Least Interference Routing (LIR), is defined which is designed specifically to operate in common-channel random-access PRNETs. The goal of LIR is to minimize the destructive interference caused along each route within the network, thus improving the spatial reuse of the common-channel. The LIR protocol calculates the potential destructive interference along each link, creates the network routing tables that minimize the potential destructive interference along an entire route, and specifies the per-packet transmission power. The implementation flexibility of each of these operations allows LIR to be implemented in a variety of radios and radio networks.

Myopic one-hop and network multiple-hop simulations indicate that dynamic power control and/or LIR improve end-to-end PRNET performance over no power control or other routing strategies, such as minimum hop routing.

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1.1 Packet Radio Networks

A packet radio network (PRNET) is a packet-switched network in which the switching elements, called packet radio units (PRUs), are connected using radio frequency (rf) channels or links [Leine87a] [Kahn78]. Therefore, a PRNET can use the traditional advantages of radio communications over wire-line communications for packet-switching. These advantages include mobile operation, easy PRNET deployment, easy PRNET addition of new PRUs, and redundancy and reliability through the broadcast nature of rf. Figure 1-1 shows a typical packet radio network structure.

Any packet-switched network that uses rf channels could theoretically be considered a PRNET. Generally, however, PRNETs are considered to be networks that apply the notion of packet-switching to radios with only a single antenna and transceiver. This would exclude any point-to-point rf packet-switched network with independent links, such as an ARPANET-like network in which there are individual transmitters, receivers, antennas, and modems for each individual rf link between switching nodes, as shown in Figure 1-2.

PRNETs provide a subnet relay or intermediate system (IS) function between higher layer network relay or end systems (ESs) functions. Therefore PRNETs lie within the lower three layers of both the International Standards Organization (ISO) Open Systems Interconnection (OSI) Protocol Reference Model [ISO84] and the Department of Defense (DoD) Internet Architecture Model [Cerf83]. This protocol relationship is shown in Figure 1-3. PRNETs typi-

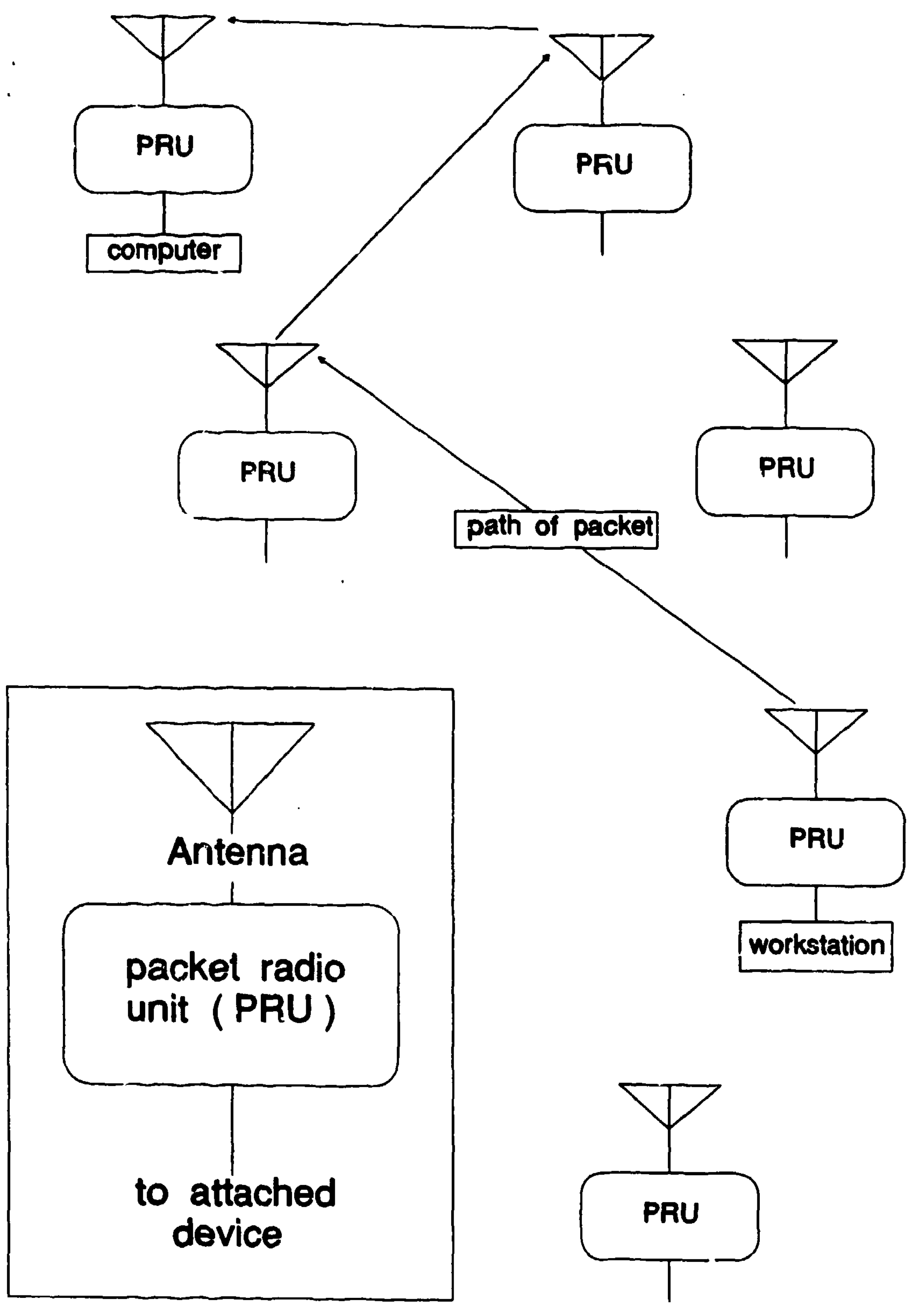

Figure 1-1. A Typical PRNET

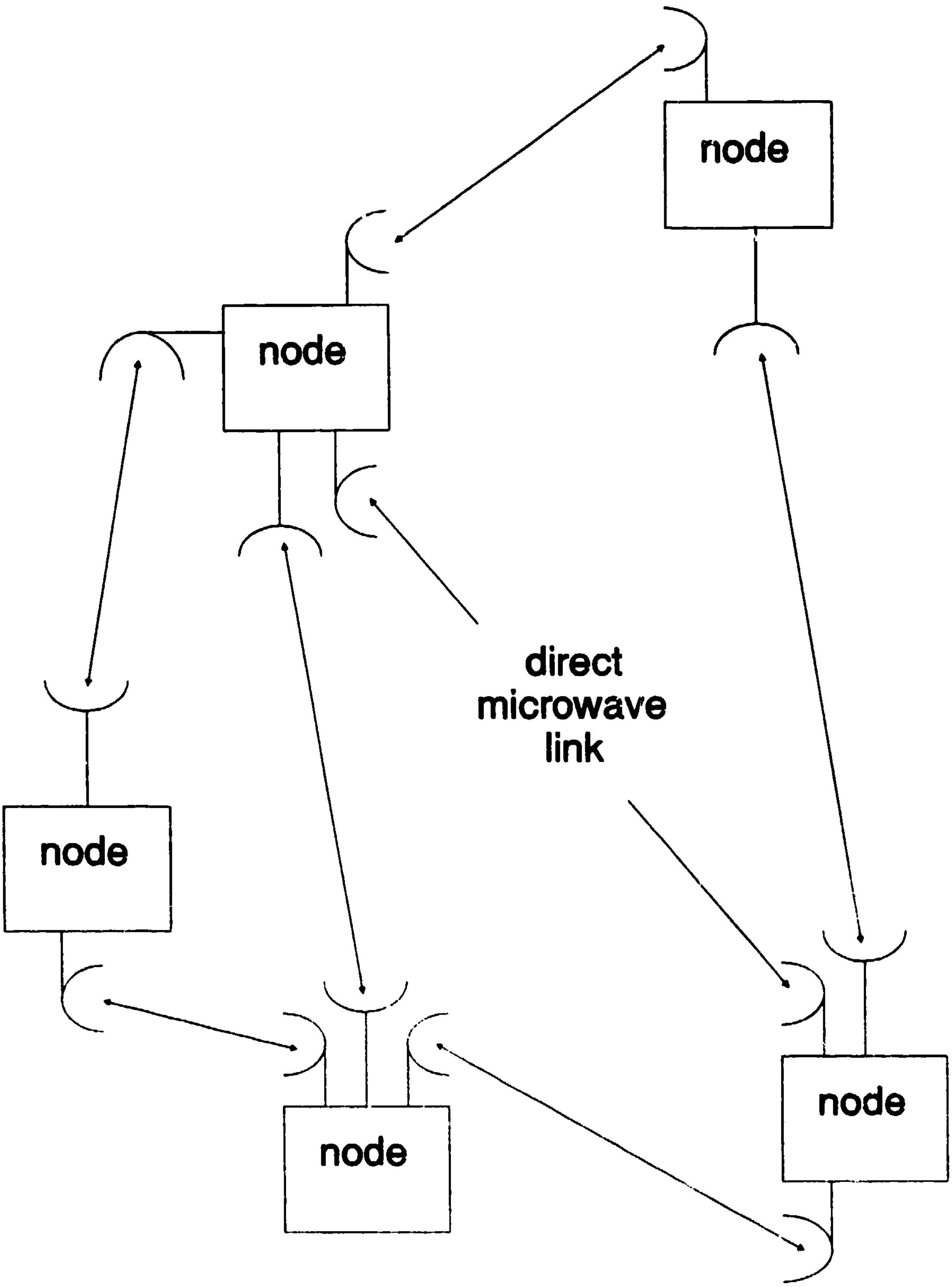

Figure 1-2. A Radio Network with Independent Links

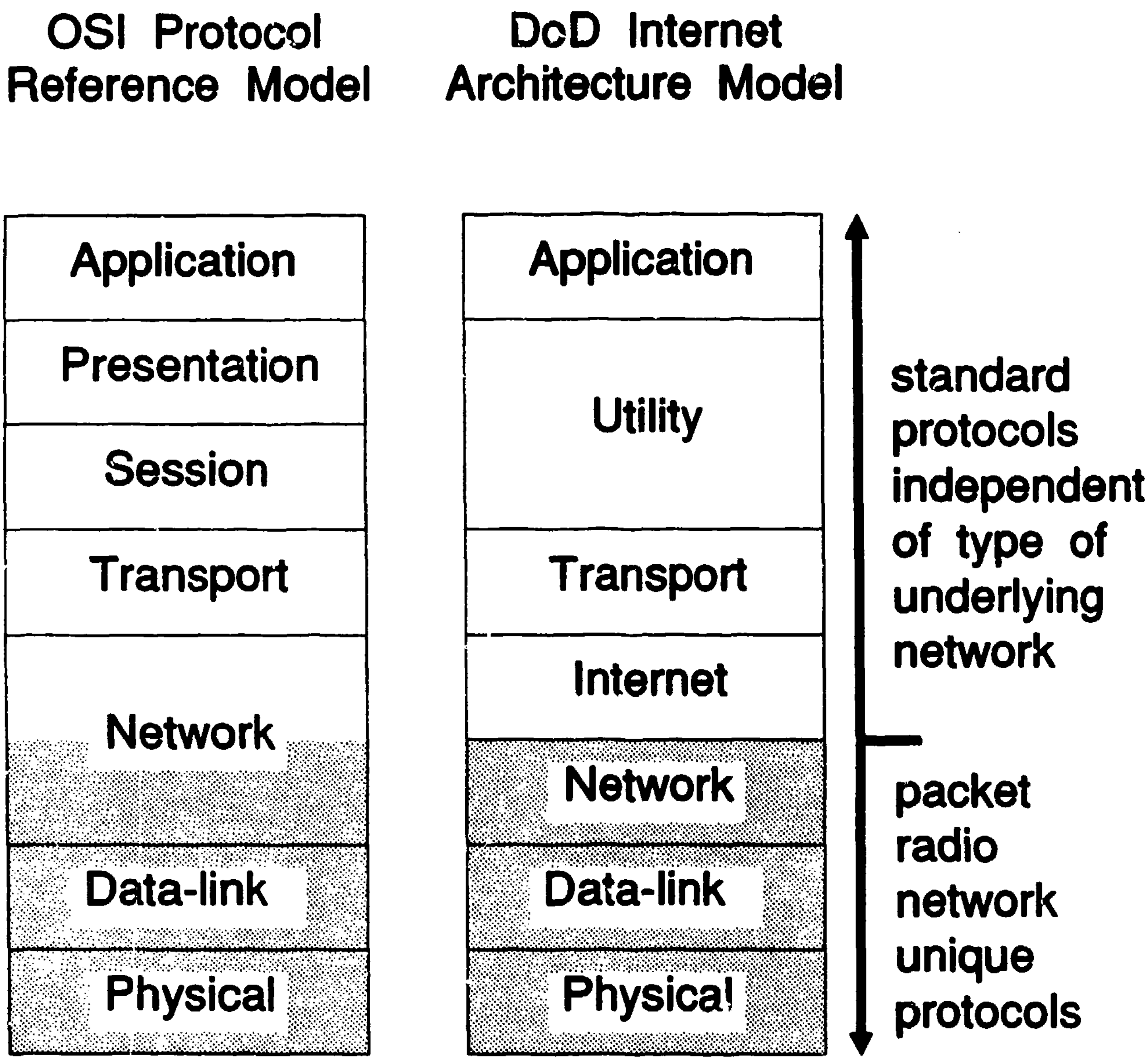

Figure 1-3. The PRNET Protocols Belong in the Lower Three Protocol Layers

cally contain unique physical, link, and network protocols specifically tailored for that PRNET.* Users of PRNETs, however, typically want to communicate with other users or resources located on other networks and thus use standard higher layer protocols, i.e., standard application, presentation, session, transport, and often (inter)network.**

In general, the layers of the protocol models were assumed to be fairly independent, and layer boundaries were created "... at a point where the description of services can be small and the number of interactions across the boundary are minimized" [ISO84]. This assumption is true in general for networks with independent links. Unfortunately, this assumption is not true for PRNETs with dependent links. The interdependence of the PRNET link and network protocol layers, coupled with the varying performance of rf channels in general, make the design of efficient PRNET protocols a difficult task. Leiner, et al, have presented an overview of the interrelated design issues in PRNETs [Leine87b].

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* Some PRNETs (typically point-to-point PRNETs) use standard protocols at the network layer. An example is the Amateur Packet Radio Network, which uses AX.25 for its network layer protocol [Karn85].

** Standard protocols are designed to work above all networks and typically assume a certain minimum network capability, e.g. minimum end-to-end bandwidth. Therefore PRNETs with a very small channel bandwidth sometimes have PRNET specific higher level protocols (typically transport) that are designed for optimized performance between users of that PRNET. An example is Simple End-to-End Protocol (SEEP), the transport layer protocol used in the Rockwell Survivable Extended Frequency HF Network (SEFN) [Mille87].

1.2 RF Channels

The rf spectrum is shared among the PRUs in a PRNET through some separation in frequency, time, or space. This sharing may be in the form of a single, common (broadcast) channel that multiple PRUs can hear and transmit on, or else in the form of many (unique) point-to-point channels between pairs of PRUs.

The PRUs that share a common broadcast channel resource transmit and listen on the same frequency, use the same rf modulation technique such as frequency modulation (FM) or amplitude modulation (AM), and typically use omni-directional antennas. Point-to-point channel resources are normally separated in frequency using frequency division multiple access (FDMA) or spread spectrum techniques, but may also be separated in space through the use of directional antennas.

A common broadcast channel resource is shared among multiple PRUs through separation in time and space. Similarly, a single PRU antenna is shared among multiple point-to-point links at a single PRU through separation in time; and a point-to-point channel resource may be shared and reused on multiple point-to-point links by multiple pairs of PRUs through separation in space.

The reuse and management of time is usually referred to as the channel access protocol [Tobag87]. Channel access protocols can be divided into two groups: contention-free and random (or contention-based). Time division multiple access (TDMA) is an example of a contention-free channel access protocol; Aloha is an example of a random-access protocol.

1.3 Common-Channel Random-Access PRNETs

In general, the implementation of mobile PRNET operation, PRNET deployment, PRNET expansion, and PRNET redundancy and reliability is easier and simpler for common-channel random-access PRNETs than for point-to-point PRNETs.

For example, it is relatively straightforward for PRUs to determine their link connectivity as they move around in a common-channel PRNET. Because PRUs share a common broadcast channel resource, it is easy for two PRUs to learn that they have moved within communication range of each other when they hear each other transmit. This task is more difficult with point-to-point PRNETs. A mobile PRU in a point-to-point PRNET must predict that it will be moving out of range of one group of PRUs and into range of another group of PRUs so that it can exchange channel information ahead of time to be able to communicate with the second group of PRUs. Alternatively, a mobile PRU can continue communicating with its older set of neighbor PRUs until it no longer can hear them. Then, the mobile PRU will have to go through a (possibly abbreviated) net entry process to find the point-to-point channel parameters of the new PRUs with which it has the potential to communicate.

The importance of common-channel random-access PRNETs can be inferred from the fact that many different operational common-channel random-access PRNETs have been built and fielded. Many of these PRNETs will be discussed in Section 2.1. Henceforth, unless noted otherwise, our discussion will be restricted to common-channel random-access PRNETs.

The performance of the common-channel can be optimized through the use of separation in time and/or space. The area of channel access techniques (time separation) has been extensively studied and a plethora of channel access protocols have been analyzed and many have been implemented [Tobag80]. The area of spatial reuse has also been studied. However, there are fewer analytical results and few, if any, operational protocols.

1.4 Spatial Reuse

Depending upon the PRNET topology and individual PRU transmission powers, PRUs can be separated in space such that certain combinations of PRUs can transmit at the same time without destructively interfering with each other. The ability to support multiple simultaneous transmissions through separation in space is called "spatial reuse" [Klein87].*

Separation in space may result from propagation loss or because one part of the network is shielded from other parts due to obstructions, such as hills or buildings, or from the nature of the radio wave propagation. A very simple model of the PRNET topology is a graph in which the vertices correspond to the PRUs and links correspond to pairs of PRUs that can successfully transmit and receive packets between each other. Such a graph lets us determine if the same rf channel frequency resource can be used on two links simultaneously without interference. Figure 1-4 shows an example of successful spatial reuse with this very simple model.

Kleinrock and Silvester present an overview of the previous analyses in their survey

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* Spatial reuse (or spatial separation) should not be confused with spatial diversity, which is a technique where two or more spatially separated antennas are used to reduce the duration and frequency of multipath fading events on an rf link, typically line-of-sight (LOS) microwave [Vigan75].

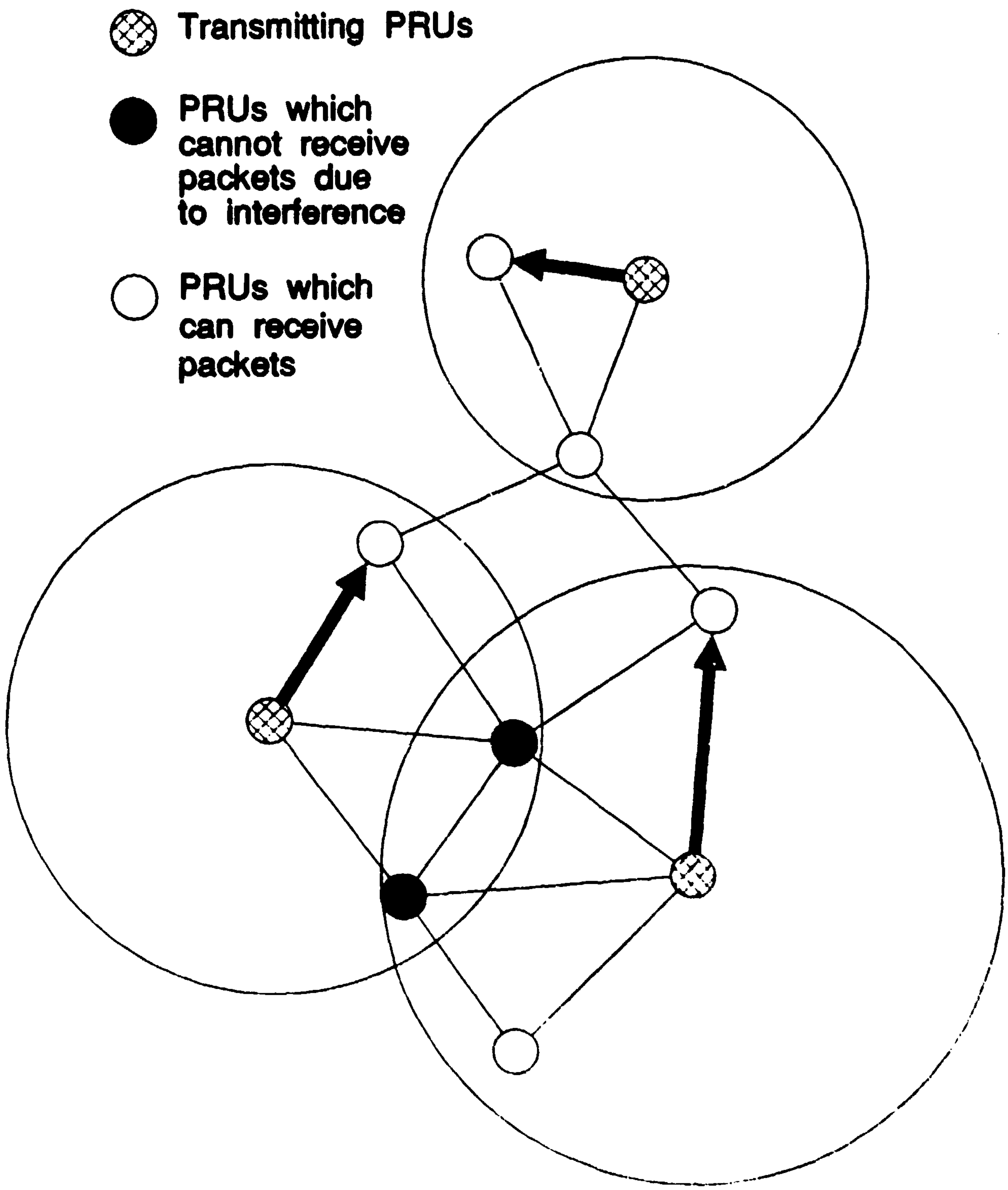

Figure 1-4. Example of Spatial Reuse in a Common-Channel PRNET

paper [Klein87]. This previous work indicated that power control is important in providing spatial reuse and increasing the performance of the common (broadcast) channel, and will be discussed in Chapter 4.

Unfortunately, the transmission strategies from this previous work, although useful for analysis, are not implementable in real networks. Kleinrock and Silvester describe the difficulty of designing protocols for spatial reuse in real networks, as follows:

> We can identify (but not solve!) several problems for continued study. ... [One] is the development of operational protocols where each node is allowed to make local decisions as to when to transmit, what power to use, and which node to select as the next node on the path to the final destination as a function of the current traffic loading. Optimal selection of (re-)transmission control parameters in conjunction with range control is an additional problem that has not been solved [Klein87].

1.5 Summary of Results

The original research presented in this dissertation includes methods of performing spatial reuse in operational common-channel random-access PRNETs through dynamic power and routing control. Simulation results are also presented comparing these algorithms to previous work in this area.

The dissertation is organized as follows: Chapter 2 will describe the structure and protocols used in packet radio in terms of operational PRNETs and some of the assumptions and models used for analysis and simulation. Chapter 3 discusses the advantages of dynamic power control, and presents some methods of performing dynamic power control in common-channel operational networks. Chapter 4 reviews the previous work performed in spatial reuse.

Chapter 5 presents a new routing protocol called Least Interference Routing (LIR) that can provide spatial reuse in PRNETs. LIR is designed specifically to operate in common-channel random-access PRNETs. The goal of LIR is to minimize the destructive interference caused along each route within the network, thus maximizing the spatial reuse of the common radio channel. Increasing the spatial reuse of the common radio channel can improve the network throughput and delay performance in general. If the PRNETs support dynamic power control, then LIR specifies the network route and the transmit power used in each hop of the route. If the PRNET does not support dynamic power control, then LIR can still provide spatial reuse through route selection.

Chapter 6 presents simulation results comparing a myopic version of LIR to the analytic transmission/routing strategies discussed in Chapter 4; Chapter 7 presents simulation results comparing LIR and minimum-hop routing in multiple-hop networks with and without power control. These simulations show the PRNET performance advantage of power control over no power control and the advantage of LIR over minimum-hop routing. Chapter 8 contains a brief summary of the results of this dissertation and presents some areas of power control and spatial reuse for future research.

2. COMMON-CHANNEL RANDOM-ACCESS PRNETS

2.1 Introduction

This section discusses operational common-channel random-access PRNETs. The discussion examines each of the three lower protocol layers of PRNETs: Physical, Data-Link, and Network. Leiner, et al, have presented an overview of the issues in operational PRNETs [Leine87b]; and Tobagi has presented an overview of the models used in the simulation and analysis of PRNETs [Tobag87].

Although there have been operational experiments with common-channel random-access PRNETs other than LOS terrestrial PRNETs [Gerla77]; long-haul PRNETs, e.g., high frequency (hf) PRNETs and satellite PRNETs, generally use point-to-point links and/or contention-free channel-access protocols. Therefore, we will limit our discussion to LOS terrestrial PRNETs.

Table 2-1 provides an overview of the most important aspects of some past and present operational common-channel random-access PRNETs. The discussion will include details from all of these networks, but most of the attention will be focused on the latest operational DARPA PRNET [Jubin87].

2.2 RF Channels

The rf channel is the PRNET physical media that provides the link connectivity between PRUs. We say that there is a link connecting PRU-A to PRU-B if PRU-B can receive

PRNET		Univ. of Hawaii Aloha PRNET	EPR/ IPR DARPA PRNET	LPR DARPA PRNET	SINC-GARS packet applique	RSRE CNR packet applique	Amateur PRNETs	Indoor PRNETs
Physical Layer	frequency	407 MHz	1.7-1.8 GHz	1.7-1.8 GHz	30-88 MHz	30-76 MHz	varies; 145 MHz typical	varies; 72 MHz typical
	ability to ctrl pwr ?	No	Yes	Yes	Yes	Yes	No	No
	num pwr levels	1	5	4	4	4	1	1
	power levels (dBm)	40 dBm	20, 25, 30, 35, 40 dBm	13, 21, 37 dBm	-3, 22, 36, 47, dBm	20, 30, 42, 47 dBm	varies	varies; 20 dBm typical
	typical max range	27 km	10 km	10 km	80 km	80 km	varies	100 m
Data-Link Layer	channel access protocol	Aloha (in channel)	CSMA (& Aloha)	CSMA	CSMA	CSMA	Aloha	CSMA
	HBH acks?	Yes	Yes	Yes	Yes	Yes & No	Yes & No	Yes
	type of HBH ack	active	active & passive	active & passive	active & passive	active & passive	active	active
Network Layer	single or mult. hop	single	multiple	multiple	multiple	multiple	multiple	single
	routing metric	na	Min Hop	Min Hop	Min Hop	Min Hop	manual source routing	na
References		Binde75	Kahn78	Jubin87 Fifer87	Lewis87 Jane88a	Davie87 Jane88b	Karn85 EST88	RayNe88 Byte88

Table 2-1. Some Operational Common-Channel Random-Access PRNETs

some minimum amount or fraction of error-free packets. Link connectivity depends upon the rf propagation and the channel-signaling method used. In general, a packet is received error-free across the link from PRU-A to PRU-B if the received rf signal at PRU-B is above PRU-B's required minimum signal-to-noise (s/n) threshold and if PRU-B is listening for the rf signal. Note that the quality of an rf link refers to the probability that a transmitted packet will be received error-free.

2.2.1 RF Propagation

RF propagation parameters affect an rf signal from the time it is transmitted to the time it is received. Major parameters include the frequency used, the distance and terrain between PRUs, the rf transmit power, the type and orientation of antennas, the noise environment, the PRNET internal noise, i.e., interference from other PRU transmissions, and the degradations of the rf signal, e.g., from multipath or fading.

2.2.1.1 Frequencies Used

Higher frequencies generally have higher bandwidth but are limited to LOS communications. Lower frequencies support lower bandwidth but may go beyond-line-of-sight (BLOS). Most common-channel PRNETs operate in the very-high-frequency (vhf) or ultra-high-frequency (uhf) ranges, i.e., 30 MHz to 3 GHz. Although BLOS communications can still occur in the lower vhf frequencies, we will limit our discussion to LOS communications.

2.2.1.2 Transmit Power and RF Power Attenuation

PRUs either have no power control, i.e., they always transmit at the same rf power level, or only a few discrete steps of power control. For example, the DARPA low-cost packet radio (LPR) has a dynamic output power range of 24 dB selectable in 8 dB steps [Fifer87].

RF signals are attenuated as they spread out through space. Two theoretical path power attenuation laws [Refer77] are the Free Space Law, where power falls off as the square of the distance, i.e.:

$$\text{Path loss (dB)} \propto 20 \log_{10} (\text{distance in kilometers})$$

and the Plane Earth Law, where power falls off as the fourth power of the distance, i.e.:

$$\text{Path loss (dB)} \propto 40 \log_{10} (\text{distance in kilometers})$$

Notice that these laws indicate that the power falls off as a function of the change in order of magnitude of the distance. In other words, the attenuation between 100 meters and 10 kilometers should be the same as between 1 and 100 kilometers. In addition to these theoretical laws, there are empirical models, such as the Longley-Rice Model [Longl68]. Figure 2-1 compares the attenuation versus distance for the Longley-Rice Model and the Free Space Law. Figure 2-2 shows a correspondence between transmission range and path loss for a dynamic distance range from 100 meters to 10 kilometers.

These laws and models imply if two receivers are the same distance from a transmitter, then they should receive the transmission at the same power level. In practice, the deployment of PRUs in actual terrain can drastically affect the rf power attenuation. For

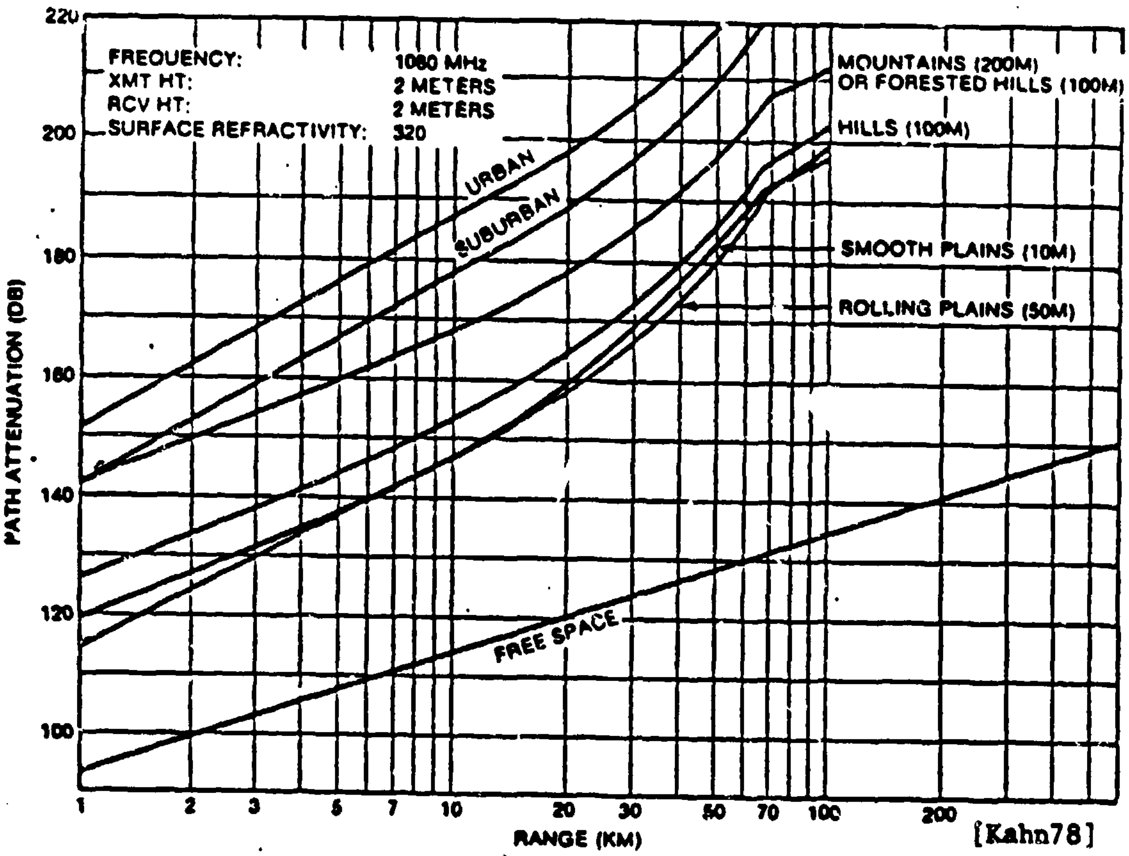

Figure 2-1. Path Loss Versus Range

Distance (kilometers)	Path Attenutation (dB) From Maximum Transmission Power		
	Free Space Law	Longley-Rice, 50m rolling hills	Plane Earth Law
100.0	0	0	0
31.6	10	12	20
10.0	20	26	40
3.2	30	51	60
1.0	40	78	80

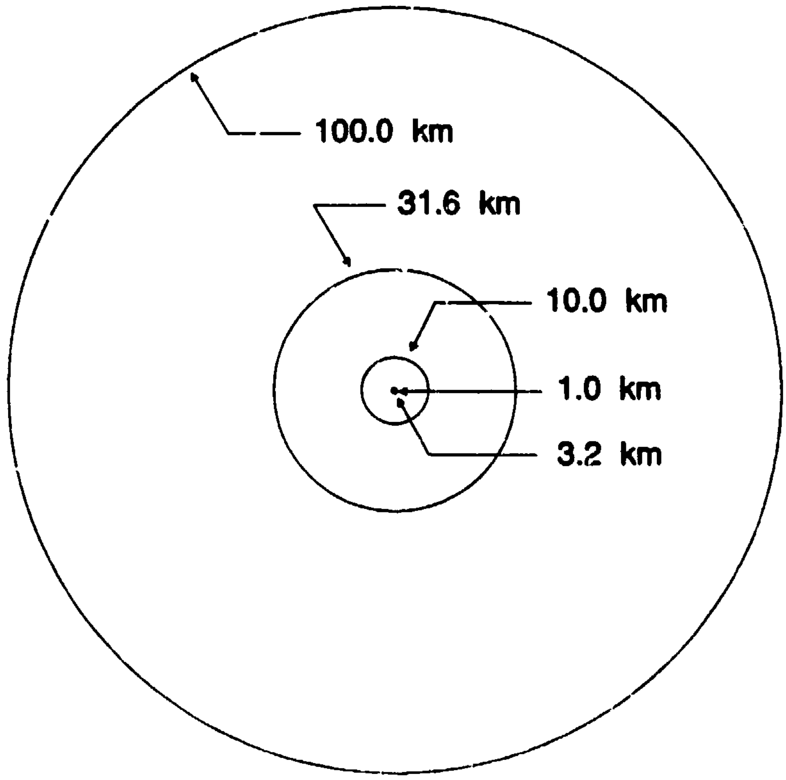

Figure 2-2. Transmission Ranges as a Function of Discrete Power Levels

example, a PRU in a gully will usually have poorer reception than a PRU on a hill. Okumura found that uhf receive power levels have a variance of up to 24 dB between receivers at the same distance from a transmitter [Okumu68]. The connectivity analysis/simulation of uhf ground based PRNETs by Sass and Brennan showed a similar range of received power levels [Sass84a] [Sass84b] [Brenn86].

2.2.1.3 Type of Terrain and PRU Siting

PRUs are normally placed where the users need them; therefore, they are not necessarily sited where the radio connectivity is the best, e.g., on top of a hill. Because it is hard to try to postulate the actual user layout, most PRNET analyses assume that the PRUs are located in either a regular or random structure. The random structure may be modeled by locating the PRUs in the plane as a Poisson process. In this case, if λ is the average density of nodes per unit area, then the probability of finding k nodes in a region of area A is:

$$Pr\{ k \text{ in } A \} = (\lambda A)^k e^{-\lambda A} / k!$$

Knowing λ, we can find the expected number of nodes, or average degree d, in a transmission range of size r:

$$d = \lambda \pi r^2$$

PRNET connectivity analysis and simulation by Sass and Brennan indicate that expected deployments of PRNETs in actual terrain show a close structural resemblance to networks generated using a Poisson distribution of nodes and fixed transmission radius [Sass84a] [Brenn86] [Sass84b]. This implies that analyses/simulations of PRNET performance using a random PRNET topology to approximate real deployments should be fairly accurate.

2.2.1.4 Antenna Type and Orientation

Omni-directional antennas radiate out equally in all directions, while directional antennas focus more of the energy in smaller volumes of space. Therefore, omni-directional antennas are especially useful for mobile PRUs. Most of the operational networks, with the possible exception of the amateur PRNETs, use omni-directional antennas.

2.2.1.5 PRNET External Noise

One of the factors that will affect the probability of correct reception of an rf signal is the noise level at the receiver. The noise level will vary in intensity with time. This variation in noise can occur over short or long periods of time. The rf signaling technique, along with an rf margin, is designed to overcome noise variations that occur over time intervals shorter than the interval to transmit a packet. Variations on the order of the packet transmission time are overcome by packet retransmissions, i.e., automatic-repeat-request (ARQ). Variations that are one or two orders of magnitude larger than the packet transmission time are overcome by increasing either the gain of the packet through reducing the data rate, strengthening the forward-error-correction (FEC) code, or increasing the transmit power level. Longer variations are overcome at the network level by determining new routes which do not use the bad link.

2.2.1.6 PRNET Internal Interference

The omni-directional propagation nature of rf signals means that rf signals transmitted from several PRUs can overlap in time at a single receiving PRU. Generally, PRUs only have a single receiver so that, at most, one of these overlapping signals can be received.

The overlapping signals interact with one another, causing distortion to the received rf signal. This interaction is called interference. Interference is said to be destructive when a receiving PRU cannot correctly receive an otherwise error free rf signal. Destructive interference that occurs to rf signals that are not intended for the receiving PRU does not degrade PRNET performance, while destructive interference that occurs to rf signals intended for the receiving PRU can degrade PRNET performance. Figure 2-3 shows an example of PRNET performance degrading interference, where the rf signal from PRU-i overlaps with PRU-j's rf signal at PRU-k such that PRU-k is prevented from receiving an otherwise error-free transmission from PRU-j.

The probability that one rf signal will cause destructive interference to another rf signal at its intended receiving PRU is the probability that the two rf signals overlap in time at the intended receiving PRU times the conditional probability that the rf signals cause destructive interference with an otherwise successful reception of the intended rf signal.

The average amount of performance-degrading interference that PRU-i could cause to the PRNET per transmission is the sum of the amount of performance degrading interference that PRU-i could cause to every other PRU in the PRNET. Using the following notation:

- I(i) = amount of potential PRNET performance degrading interference caused by a PRU-i transmission, where I(i) is a sum of several probabilities and thus can be greater than 1
- I(i,k) = amount of potential performance degrading interference a PRU-i transmission causes to otherwise successful receptions by PRU-k

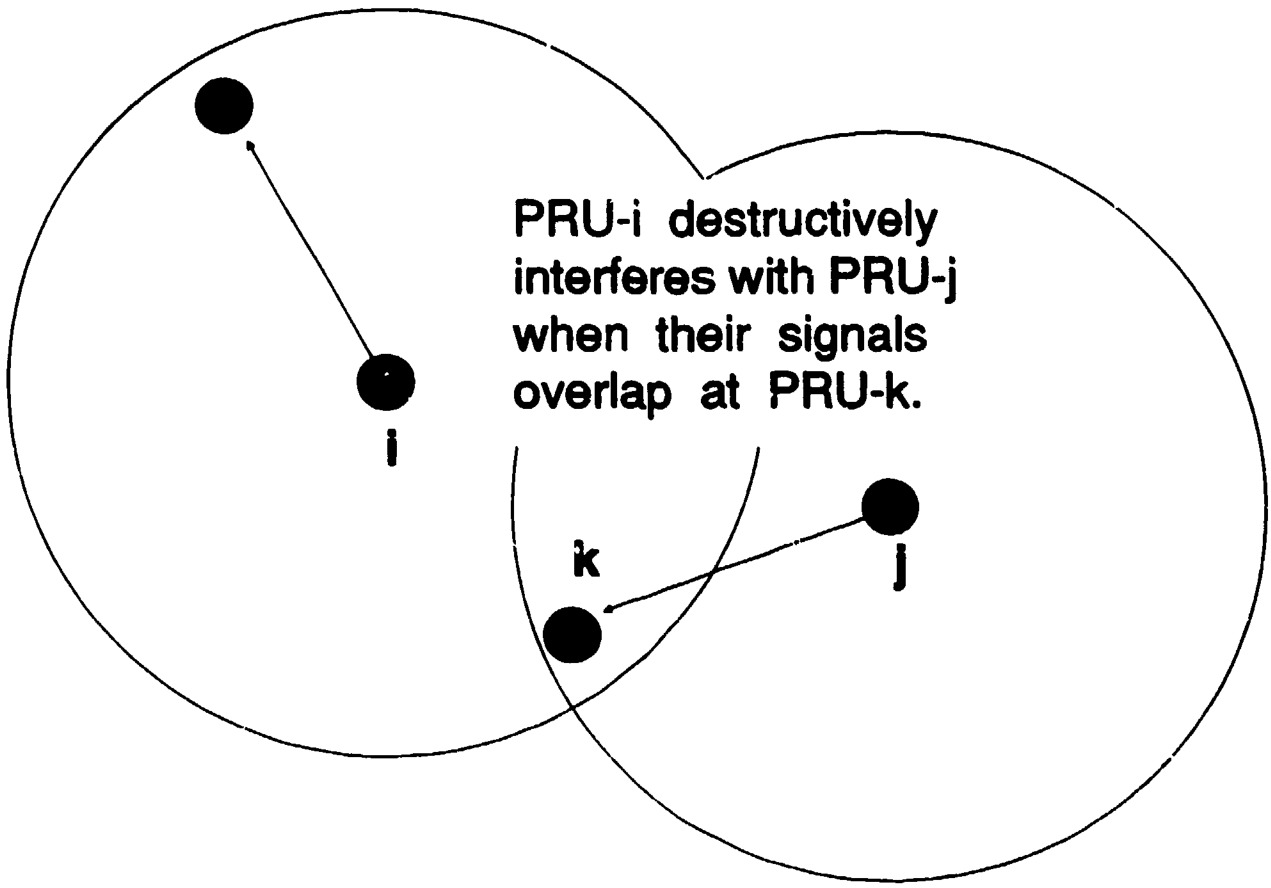

Figure 2-3. Example PRNET Performance Degrading Interference

I(i,j,k) = conditional probability that a PRU-i transmission causes destructive interference with an otherwise successful transmission from PRU-j to PRU-k, given that the PRU-i and PRU-j rf signals overlap in time at PRU-k

O(i,j,k) = probability that the rf signals transmitted by PRU-i and PRU-j overlap in time at PRU-k

we can say that:

$$I(i) = \sum_k I(i,k) = \sum_k \sum_{j \neq i,k} O(i,j,k) \bullet I(i,j,k)$$

Performance-degrading interference can be reduced by making O(i,j,k) or I(i,j,k) small. Contention-free channel access protocols are designed so that O(i,j,k) ≅ 0, while contention-based channel access protocols are designed so that O(i,j,k) < k where k is some positive upper bound less than 1. In addition, in multihop PRNETs there usually exist some PRUs that are separated in space so that I(i,j,k) ≅ 0.

Point-to-point rf channels alleviate but do not eliminate interference. For example, code division multiple access (CDMA) allows a PRU receiver to correctly demodulate or "capture" one of several overlapping and partially nondestructive interfering rf signals [Pursl87]. However, if the net power of overlapping rf signals becomes greater than some threshold, destructive interference occurs and the PRU cannot receive an rf signal correctly.

In general, however, as shown in Table 2-2, there will be more performance degrading interference between links in a common-channel random-access PRNET than there will be for PRNETs using point-to-point or contention-free channels.

		channel access	
		contention-free	random-based
rf channel	point to point	$O(i, j, k) \cong 0$ $I(i, j, k) \cong 0$ $\longrightarrow I(i) \cong 0$	$I(i, j, k) \cong 0$ $\longrightarrow I(i) \cong 0$
	common	$O(i, j, k) \cong 0$ $\longrightarrow I(i) \cong 0$	$O(i, j, k) > 0$ $I(i, j, k) > 0$ $\longrightarrow I(i) > 0$

Table 2-2. Interference and Type of PRNET

2.2.1.7 RF Signal Degradation

RF signals are subject to variations in attenuation of signal strength along a path. This attenuation is called fading. For example, rf signals are subject to multipath, where copies of a signal take different length paths and arrive at the destination out of phase, thus interfering with each other. Multipath fading is frequency dependent. In addition, changes in refractive index also give rise to flat fading.

The fading time interval can be overcome through the same measures as mentioned in Section 2.2.1.5 for overcoming external noise. A useful antimultipath technique is to reduce the data rate to reduce the amount of overlap of digital symbols at the receiver, at the expense of larger transmission times. Other antimultipath methods do not have this cost, e.g., adaptive equalization, but may be hard to apply in burst, i.e., packet, systems.

2.2.2 Channel Signaling Method

There are two basic signaling methods used by PRNETs: narrow-band and wide-band (or spread spectrum) signaling.

2.2.2.1 Narrow-Band Channel Signaling

Narrow-band channel signaling modulates the data bits directly onto the rf carrier through FM or AM. Therefore, the overlap of two packets at some receiver with nearly the same power level results in the mutual interference and loss of both packets. If the two packets had widely different power levels, then the more powerful packet could be received correctly through some form of power capture. Thus, PRNET-generated interference may be reduced somewhat using capture mechanisms. Most operational PRNETs have some limited amount of capture.

2.2.2.2 Wide-Band Channel Signaling

Wide-band channel signaling generally refers to the use of spread spectrum techniques [Pursl87] but also includes FM. Wide-band FM has a much greater amount of capture than does narrow-band FM.

Spread spectrum is based on some form of coding of the data bits and uses a much wider bandwidth than does narrow-band signaling for the same data rate. Two different spread spectrum signaling operations include direct sequence pseudo-noise (PN) modulation and frequency hopping (FH). In general, spread spectrum meets several PRNET performance needs, including (1) code division, (2) time capture, (3) antimultipath, and (4) protection against narrow-band interference. Code division refers to the fact that multiple transmissions with orthogonal spread spectrum codes may overlap in time with little or no effect on one another. Time capture refers to the ability of an idle receiver to successfully receive a packet with a given code despite the fact that other packet transmissions may overlap in time with the same or different codes.

The interference term $I(i,j,k)$ is much more complex for the spread spectrum case than for the narrow-band case. In particular, the interference depends upon the type of spread spectrum signaling used. For example, some of the different types of signaling depend upon the codes used in the preamble and may be space-homogeneous, receiver-directed, or transmitter-directed. In general, we may assume that spread spectrum systems cause much less interference than narrow-band systems.

2.3 Link Protocols

The PRNET link protocols are concerned with the communications between adjacent PRUs. (Two PRUs A and B are considered to be adjacent if PRU-A can hear PRU-B's transmissions or PRU-B can hear PRU-A's transmissions.) Important parts of the link protocols include the channel access protocols, the link determination and control, and the packet transmission and retransmission protocols.

2.3.1 Channel Access Protocols

As discussed in Section 1.2, the channel access protocol describes how PRUs access the common-channel in time. There are two basic types of random-access channel access protocols: the Aloha type and the carrier sense type. Each of the two types has several variants.

Basically, a PRU will attempt transmission of a packet at random points in time. Packets scheduled for transmission that are inhibited by the operation of the channel access protocol will be considered again for transmission at some future point in time.

2.3.1.1 Pure Aloha

In pure Aloha, a PRU is allowed to transmit only if it is not already transmitting [Abram70]. The PRU does not care about the state of the channel in the network. Note that pure

Aloha implies that the reception of a packet by a PRU will be aborted if that PRU schedules a packet for transmission during the time of the reception. In other words, transmissions have priority over receptions.

2.3.1.2 Disciplined Aloha

In disciplined Aloha, a PRU is allowed to transmit as long as it is not already transmitting or receiving a packet. Therefore, disciplined Aloha implies some sort of limited channel sensing that leads to improved performance. Most operational common-channel random-access PRNETs using Aloha use the disciplined variant of Aloha.

2.3.1.3 Slotted Aloha

In slotted Aloha, the time axis is considered to be universal for all PRUs and is divided into equally sized slots. The time slot is just large enough so that the transmission time of the largest packet plus the largest propagation time will fit into one slot. The PRUs that have packets scheduled for transmission in a slot will transmit their packets at the beginning of the time slot. Slotted Aloha doubles performance over pure Aloha because the probability of packet overlap is reduced by half. However, slotted Aloha requires that PRUs have synchronized clocks.

2.3.1.4 Carrier Sense Multiple Access

In carrier sense multiple access (CSMA), PRUs sense the channel before transmitting to see if any of their neighboring PRUs are transmitting. A packet will be transmitted only if the node is not already transmitting and no ongoing transmissions are sensed. CSMA provides dramatic improvement over Aloha in a single hop network where every PRU can hear every other PRU. The CSMA performance is degraded down to almost that of Aloha in dense multihop networks where there are hidden PRUs. CSMA may or may not be possible in spread spectrum systems, depending upon the type of spread spectrum signaling used.

2.3.1.5 Busy Tone Multiple Access

Busy tone multiple access (BTMA) is designed to alleviate the problem of collisions caused by hidden PRUs. In BTMA, a PRU will emit a tone on a separate channel to indicate that it is currently receiving a packet. The busy tone is then used to inhibit the receiving PRU's neighbors from transmitting and thereby interfering with reception. BTMA is less attractive than Aloha or CSMA because of the extra bandwidth and hardware requirements of the activity-signaling channel.

2.3.2 Link Determination and Control

Link connectivity is determined by information gathered by the two PRUs at either end of the link.* Typically, this information is exchanged by the two PRUs to determine the link quality. The goal of the link is to support some minimum rate of packets in a bi-directional man-

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* Note that although it is possible to predict average effects of terrain and distance through the use of detailed topological maps, the knowledge of PRU positions, and the use of an rf propagation model; in practice, this information cannot be used to engineer individual links [Holli88].

ner. Although protocols exist for the use of uni-directional links [Steve86] [Gerla83], they are not used in routing in operational PRNETs.

The link quality is a function of the link measurements that the PRUs can make. One method of determining the link quality is to make rf channel measurements such as signal level, s/n ratio, and bit error rate on a per packet basis. These measurements can then be integrated over several packets to determine the link quality. Another method is to make measurements at the data-link layer. This is performed by counting the percentage of packets that are received correctly over some period of time. The problem with this method is that it typically requires a longer period of time than do direct measurements of the rf channel. Another advantage of direct rf measurements over the data-link measurement is that it is often possible to make predictions for several different sets of parameters based upon the results from one set of parameters. For example, by knowing the received signal level corresponding to one transmit power level, it may be possible to predict the receive signal level for another transmit power level. The link information is typically stored in what is known as the PRU neighbor table [Jubin87].

2.3.3 Packet Transmission and Retransmission Protocols

Packet transmission protocols have to decide when to access the channel, i.e., offer packets to the channel access protocol, as well as decide what radio transmit parameters to use. Generally, the transmit parameters are chosen from the PRU neighbor table based upon the link measurements.

An rf channel has a noisy environment compared to wire-lines. Thus, PRNETs usually use some sort of hop-by-hop acknowledgment with hop-by-hop retransmissions to provide a high degree of probability that a packet will correctly reach its destination. The broadcast nature of common-channel PRNETs means that PRUs can use a "passive" or "echo" hop-by-hop acknowledgment, which occurs naturally when a previous PRU in a route can overhear the next PRU in a route forward a packet. Alternatively, PRNETs can use "active" acknowledgments in which a specific acknowledgment packet is sent by a receiver PRU back to a transmitter PRU. Relay PRUs can use either passive or active acknowledgments, while destination PRUs can use only active acknowledgments.

When an acknowledgment is not received and a packet must be retransmitted, it means that either:

(1) The previous packet was interfered with.

(2) The noise, including jamming, has increased at the receiver.

(3) Fading is occurring on the channel.

(4) The destination is moving into a position having poorer connectivity (such as away or down into a valley).

(5) The acknowledgment was lost (due to collisions, increased noise, fading, etc.).

(6) The next PRU is congested so that it either had to discard the received packet or else has stored the received packet in its queue and the packet has not yet been transmitted.

(7) The next PRU is down, e.g. powered-off or failed in some fashion.

Therefore, retransmission algorithms generally increase the delay between transmissions to reduce congestion and also modify the rf transmit parameters (such as data rate or FEC coding rate) in order to increase the gain at the receiving PRU as discussed in Section 2.2.1.

To avoid channel stability problems, operational PRNETs will usually employ some sort of algorithm that determines when the PRUs try to transmit packets. For example, the DARPA PRNETs employ an algorithm called "pacing" [Jubin87] [Gower82].

At some point, the transmitting PRU may decide that the link has gone away completely. At this point, the transmitting PRU can either try to perform alternate routing to the destination via some other PRU(s) [Jubin87] or discard the packet.

2.4 Network Protocols

Routing protocols determine how to forward and relay packets through a multihop PRNET to the destination. Note that routing is not required for single hop PRNETs, but is required for multihop PRNETs.

Typically, the routing calculation is performed automatically using a minimum-hop routing metric. However, the amateur PRNETs use manual source routing, where the human operator has a list of the typical connectivity of the amateur PRUs and thus puts the desired route into the header of the packet. Each PRU, called a "digipeater" in the amateur PRNET, will read the route and forward on the packet on to the next "digipeater" in the route.

A shortest path routing algorithm is run using the routing metric as the cost function. The shortest path routing algorithm can be either centralized or distributed. Three operational shortest path routing updating methods are:

(1) A centralized routing method in which a single PRU obtains all link information, calculates the network routing tables, and distributes the network routing tables to every PRU in the PRNET [Kahn78].

(2) A distributed routing method in which all link information is broadcast to every PRU in a PRNET and each PRU then calculates the routes, similar to the new ARPANET routing algorithm [McQui80].

(3) A distributed incremental routing method in which each PRU broadcasts its network routing tables and its neighbor PRUs incrementally calculate their own routes [Westc82] [Jubin87].

The output of the routing algorithm is a routing table for each PRU in the network. The routing table contains every PRU in the PRNET, along with the next PRU in the route to that destination. Once the routing tables are built, packet forwarding typically proceeds as follows: A PRU receives a packet (from either the rf channel or the wire channel to an attached device). The PRU looks at the packet header to see if it is the destination. If the PRU is the destination, it processes the packet or gives it to its attached device. If the PRU is not the destination, it looks in its routing table to determine the next PRU, and hands the packet to the data-link layer for transmission on the rf channel to forward the packet to the next PRU.

3. DYNAMIC POWER CONTROL

3.1 Importance of Power Control

Because the probability of reception of an rf signal at a receiver is dependent upon the strength of that signal's rf power, the goal of power control is to use as little power as possible and still have a high probability of good reception. Because the attenuation of rf channels and the strength of interfering noise signals can change rapidly with time, an efficient power control method must be dynamic in operation.

As pointed out in Section 2.2.1.2, power control is the dominant rf parameter that PRUs in a common-channel PRNET can vary to adjust their transmission range. As noted in Section 1.4, the modification of transmit ranges, especially through power control, plays an important part in performing spatial reuse in common-channel PRNETs.

However, power control is important for other reasons than spatial reuse. Section 3.2 will discuss several uses of power control in radio networks in general, i.e., in both common-channel and point-to-point channel PRNETs. Section 3.3 will discuss methods of performing power control in any radio network. Section 3.4 will then discuss how to implement power control in the transmission protocols of common-channel PRNETs.

3.2 Uses of Dynamic Power Control in Radio Networks

This section discusses the importance of (dynamic) power control in radio systems in general. Even though the discussion is general in nature, all of the points considered are relevant to packet switching over rf channels.

3.2.1 Increase Spatial Reuse

As discussed in Section 1.4, spatial reuse means that more than one transmission on a single channel can take place at the same time without destructive interference. Spatial reuse is important for efficient operation in common-channel PRNETs. Spatial reuse is also important for point-to-point networks. Government restrictions on the use of the rf spectrum limit the number of available channels. Spatial reuse increases the number of point-to-point links that can exist on a limited set of channels.

Some examples of operational point-to-point networks that use spatial reuse of rf channels are cellular radio [Erlic79] and common-carrier microwave channels [Bates87]. Although the cellular radio cells and the common-carrier networks can be engineered to provide spatial reuse without dynamic power control, additional spatial reuse can provide additional communications capability in these increasingly crowded radio systems [Nagat83] [Jaege86].

3.2.2 Decrease I rference

The channels in point-to-point radio networks are generally considered to be unique and independent from one another, as shown in the simple conceptual diagram in Figure 3-1A which illustrates several adjacent frequency channels. In actual practice, this is not true because of the rf spectral side lobes shown in Figure 3-1B. In Figure 3-1C, because the receiver of signal B on channel B is close to the transmitter of signal C on channel C, it is possible that the side

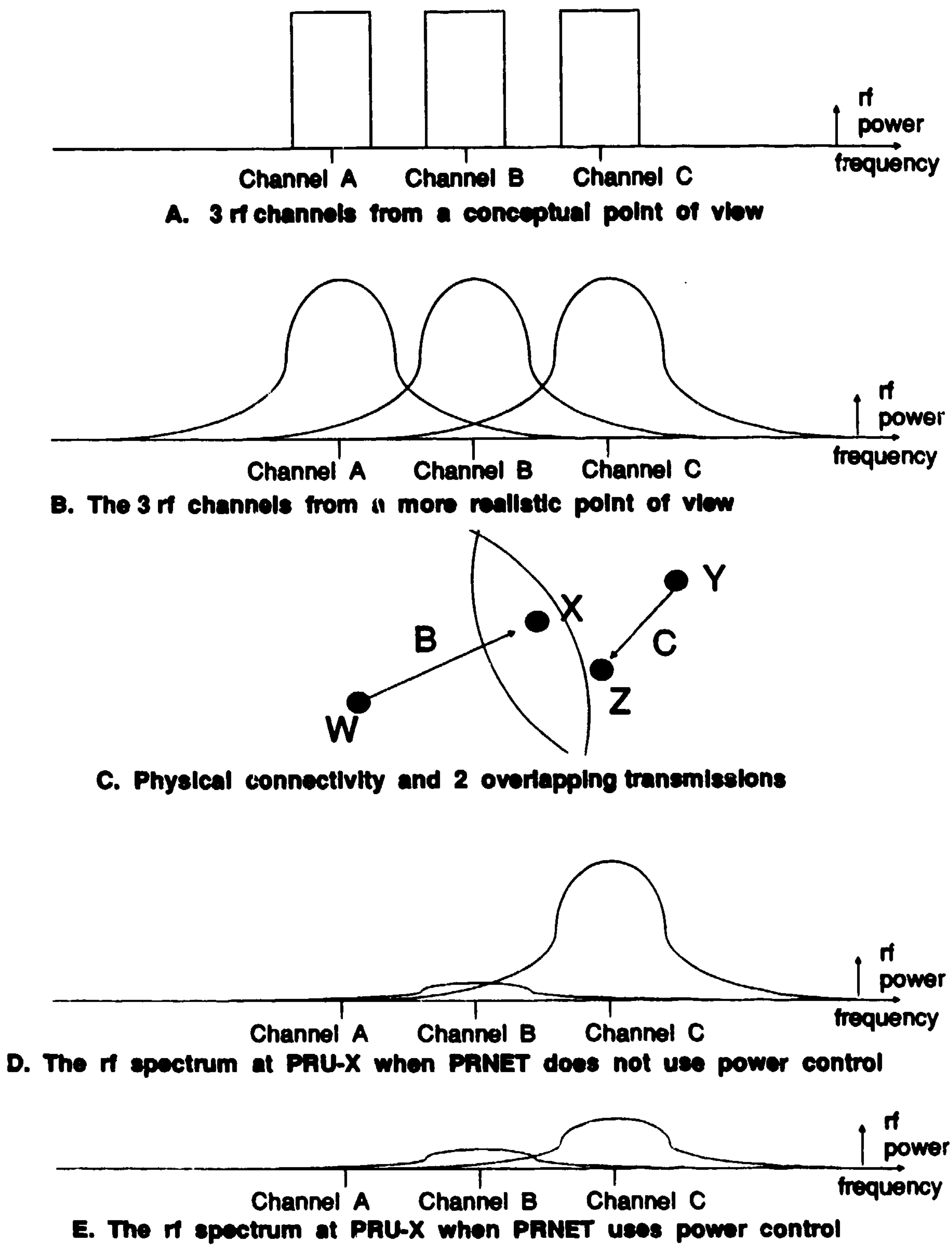


Figure 3-1. Power Control and Adjacent Channel Interference

lobe of signal C could be larger than the main lobe of signal B, thus causing interference as shown in Figure 3-1D.

Interference between two point-to-point channels is called "adjacent channel" interference. Interference caused by an imbalance in signal strength due to differences in distance is called a "near-far" problem. Note that "near-far" problems can occur in common-channel radio networks that have FM or spread spectrum capture capability. FM capture refers to the ability of a receiver to correctly receive the strongest of several interfering signals; spread spectrum capture refers to the ability of a receiver to lock on to the first signal to arrive so that later signals look like noise and can be rejected [Pursl87].

Returning to Figure 3-1C, we see that transmitter Y did not have to transmit with the same transmit power as transmitter W because Y's destination is closer to Y than W's destination is to W. Figure 3-1E shows that with dynamic power control it could have been possible for X to have correctly received W's transmission.

Automatic dynamic power control has been used to reduce adjacent channel interference in point-to-point networks for almost 30 years. Perhaps the first radio network to use automatic dynamic power control was the Collins Radio High Capacity Communications (HICAPCOM) experimental network for the U.S. Navy in 1961 [Bagle88]. Dynamic power control has been proposed [Alavi82] [Rosen85] [Viswa82] and tested [Nagat83] for use in cellular radio systems; has been implemented in the British Ptarmigan Single Channel Radio Access (SCRA) system [Thomp78]; has been proposed and tested on satellite up-links [Yamam82]; and has been used on some common carrier microwave links [Ramir86].

Analysis of spread spectrum systems indicates that dynamic power control should help alleviate the spread spectrum "near-far" problem for point-to-point links [Skaug82] [Ormon82]. Turin has analyzed the effects of "near-far" problems on transmitter and receiver directed spread spectrum systems, and suggests that although power control helps eliminate "near-far" problems for some network connectivities, such as a star, it probably will not help the case of a dense network [Turin84].

3.2.3 Decrease Interference to Other Systems

Different radio systems are generally assigned different frequency bands. However, interference between networks can occur just as adjacent channel interference can occur between unique channels in point-to-point networks. Therefore, reducing transmit power in general should help reduce the interference to other systems.

Johnson describes an operational hf radio system that was specifically designed with dynamic power control to reduce interference to other systems [Johns78]. The system linked together oil rigs in the North Sea to the European mainland. Dynamic power control allows the system to reduce the interference caused to existing European radio systems.

3.2.4 Decrease Probability of Detection/Interception

The detection and interception of military communications are an important part of electronic warfare (EW). Therefore, military communications systems desire to radiate with as little rf power as required to communicate. Dynamic power control allows the rf power level to be as small as possible and still support communications in a changing rf environment.

3.2.5 Decrease Electrical Power Demands

Many radio systems, especially mobile radio systems, operate using battery and/or solar power. The use of dynamic power control would allow these systems to operate for longer periods than if they just operated at peak rf power.

Satellite networks are often power limited. Therefore, routing based on a metric function of the transmit energy per bit, congestion and delay, and satellite battery status has been proposed for use in the Multiple Satellite System (MSS) [Qual 87].

Dynamic power control has been analyzed [Longh75] [Engla79] [Tebbe84] and tested [Harri84] to gain more channels in repeater satellites. The frequency used for satellite down links is attenuated by precipitation so that existing satellite systems always transmit with an extra 3 to 6 dB of margin to overcome the rain attenuation. At any given period of time, however, most links are not being degraded by rain. Therefore, dynamically reducing the rf margin on clear sky links, i.e., selectively increasing the transmit power for the down links with rain at the earth station, provides additional rf power that can be used to operate additional rf channels.

3.2.6 Increase RF Power Margins

Operation of rf links at maximum power eliminates one dimension of adaptivity that radio systems could have. For example, suppose that a radio system could lower the rf power on all of its links by some amount. This additional rf power could be used to provide for new or additional communications services. For example, higher priority packets could be transmitted at a higher power level than lower priority packets, thus preempting the lower priority packets in the rf channel [Bebee88]. Traditionally, the way to provide precedence in an Aloha rf channel is to adjust the position of packets in the different PRU transmit queues. These traditional schemes do not provide a way for higher priority packets in one PRU to preempt lower priority packets at other PRUs. However, the adjustment of power based upon packet priority could be a workable scheme for PRNETs with FM capture. (Remember that with FM capture, a receiver will generally receive the strongest of several overlapping signals, although the issue is complicated by the packet arrival order and preamble processing mechanisms.)

3.2.7 Decrease RF Environmental Impact

RFs between the frequencies of 100 MHz and 100 GHz are considered to be microwave radiation. American National Standards Institute (ANSI) standards provide guidelines on the acceptable limits of human microwave exposure. This limit is 10 mW/cm^2 for periods of 0.1 hour or more. Note that a 0.1 watt microwave source is safe at a distance of a centimeter or more from the radiating source, while a 1 watt source is only safe at a distance of 3 or more centimeters from the radiating source [Weigl73]. Therefore, it is conceivable that a hand held radio system might operate at two power levels, depending upon whether it was sitting on a shelf or desk or whether it was being held or carried by a person.

The combination of electromagnetic interference problems affecting computer equipment as well as the inconclusive, but growing, evidence of medical problems from electromagnetic waves other than microwave, suggest that it would be a prudent communications system design practice to limit transmit power to just that needed for communications [Jenki88].

3.3 How To Perform Dynamic Power Control in General

Dynamic power control can be implemented as either a closed or open loop system. An open loop system assumes that the two one-way links between radio nodes are related so that the measurement of the signal in one direction can be used to adapt the transmission of the signal going back the other way. This assumption may be poor when the problem is caused by jamming or interference. A closed loop system does not assume that the two one-way links are related, thereby requiring that the measurement be fed back to the transmitting radio node for use in adapting its power level.

If an rf signal is not received correctly, a receiver may be able to determine that the rf signal was generated by one of the transmitters in the radio system, but the receiver will not be able to identify the transmitter. (This assumes that the rf signal is not physically unique in some identifiable way such as in frequency or spread spectrum code used.) Therefore, connectivity at maximum power will probably have to be measured directly and cannot be predicted based upon the connectivity at lower power levels. Conversely, however, a system may be able to predict the connectivity of lower power levels based upon the connectivity at higher power levels.

Some full duplex microwave links are able to dynamically adjust the power in the face of fast fades [Ramir86] through the use of real-time measurement being fed back to the transmitter. Other channels have longer delays, so that they cannot respond fast enough to operate through fast fades. Therefore, power control will only work for slow fades, such as occurs with rain attenuation or some Rayleigh fading.

The link quality measurements required can vary from the very simple to the complex. The link quality measurements will be similar to those described in Section 2.3.2.

3.4 How To Perform Dynamic Power Control in Common-Channel PRNETs

Several generations of the DARPA packet radios have had the ability to dynamically control power. However, this capability has been unused because of a lack of network control algorithms. The lack of network control algorithms arises from the fact that the links between PRUs are not independent. In addition, some analysts had a conceptual problem that all of the PRUs had to adaptively change their power levels in unison, i.e., the network power control algorithm had to determine the single optimum transmission power to use throughout a PRNET instead of allowing each PRU to pick its transmission power on a packet-by-packet basis.

Shacham and Westcott, in their overview of future research areas in packet radio, examined the dynamic setting of radio parameters. They concluded that, "More research is needed to provide an adaptive power control under realistic operating conditions" [Shach87].

This section describes some ways that dynamic power control can be used by existing link layer protocols described in Chapter 2, for common-channel PRNETs. Chapter 5 will describe a network layer protocol that can explicitly take advantage of power control to optimize the network connectivity.

PRUs will still need some sort of broadcast mechanism and return feedback path to determine neighbor connectivity. PRUs will always have to broadcast a few times at their greatest possible power level to determine the possible connectivity, even if the PRUs will not normally use their greatest possible power level. Depending upon the type of rf measurements available, the PRUs can then either predict what the connectivity will be like at lower power levels or the PRUs can use a broadcast mechanism to determine neighbor connectivity at several power levels. The minimum power required to reach each neighbor with some minimum level of acceptability will then be stored in the PRU neighbor tables. Note that the minimum power required to reach each neighbor with some minimum level of acceptability will probably include an rf margin to provide protection against fluctuations in environmental noise and fading.

Depending upon whether the power control is implemented as an open or closed loop, the actual transmit powers may or may not have to be calibrated.

Figure 3-2 shows an example 10 node partially connected PRNET within a 50-by-50 kilometer square. If we use the threshold hearing model to represent the rf channel and power propagation loss, Table 3-1 shows a portion of several possible Neighbor Tables for PRU-10. The threshold hearing model assumes that if two PRUs are closer than a certain threshold distance (or transmission range), then they are able to communicate (without errors) with probability 1. Otherwise, if the two PRUs are farther apart than the threshold, they are unable to communicate, i.e. will communicate with probability 0. The maximum PRU transmission power level is assumed to only allow PRUs to transmit up to 10 kilometers away. The transmission attenuations shown in Table 3-1 were obtained using the Free Space Law.

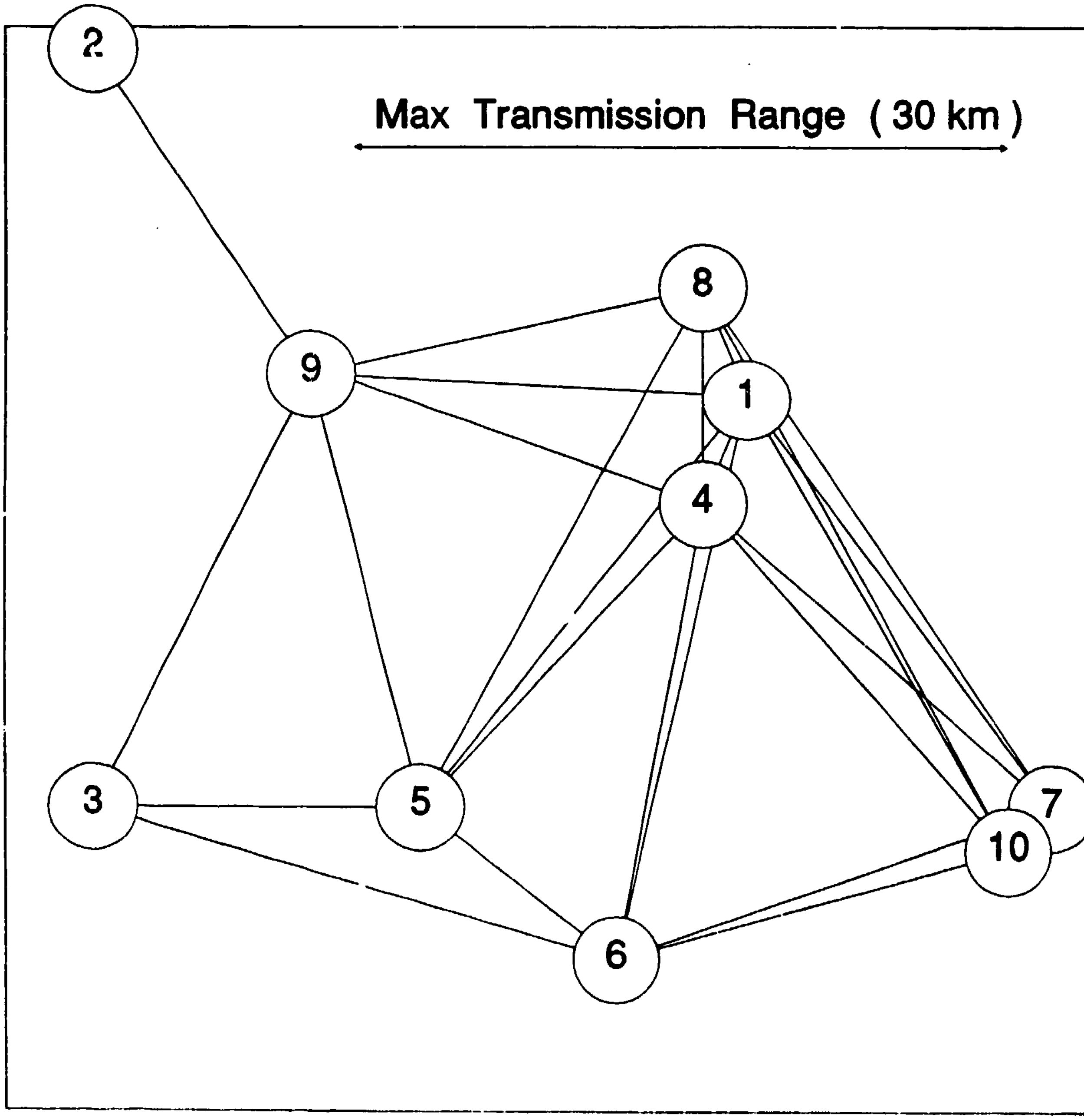


Figure 3-2. Example 10 Node Partially Connected PRNET

Neighbor PRU	Distance (km)
1	24.19
4	21.26
6	18.97
7	2.83
8	29.53

A. Neighbor Table When Using a Constant Transmit Power

Neighbor PRU	Distance (km)	Attenuation (dB) from max power
1	24.19	1.9
4	21.26	3.0
6	18.97	4.0
7	2.83	20.5
8	29.53	0.1

B. Neighbor Table When Using Continuous Dynamic Transmit Power Control

Neighbor PRU	Distance (km)	Good link at following (dB) attenuations from max power			
		0	3	9	27
1	24.19	Y	N	N	N
4	21.26	Y	Y	N	N
6	18.97	Y	Y	N	N
7	2.83	Y	Y	Y	N
8	29.53	Y	N	N	N

C. Neighbor Table When Using Discrete Dynamic Transmit Power Control

Table 3-1. PRU-10's Neighbor Tables for 10 Node PRNET in Figure 3-2

The current PRNET routing algorithm, e.g., minimum-hop routing, can continue to run as before without being concerned that power control will be used at the link level. Therefore, when forwarding packets, the PRUs will still look up the destination PRU in the routing table to determine the next PRU, and then look up the next PRU in the neighbor table to learn what transmission parameters to use. The difference is that transmit power is now one of the transmission parameters and packets will be transmitted with just enough power to reach the next PRU. If the transmission is a multi-cast transmission, then the transmit power that should be used is the maximum of all of the minimum transmit powers needed to reach each of the individual PRUs. A multi-cast is a single transmission with several next destination PRUs as compared to the normal uni-cast case with a single next destination PRU [Caple87] [Liu81].

This simplification does not take into account passive acknowledgments. Because a transmission is expected to reach both the previous and next PRUs, a relay PRU should look up both PRUs in the neighbor table and transmit with the maximum of the two listed transmission powers. Naturally, the source PRU would only look up and use the power required to forward a packet on to the next PRU, and the destination PRU would only look up and use the power to send an active acknowledgment back to the previous PRU. Similarly, if a relay PRU were to send an active acknowledgment, it would only look up and use the power required to reach the previous PRU.

In addition, if the PRUs normally do not transmit at maximum power. then dynamic power control gives them one extra parameter that can be varied when retransmitting unacknowledged packets. As discussed in Section 2.3.3, when a packet has to be retransmitted, it means that either the previous packet was interfered with, part of the PRNET is congested, or the link quality has decreased. As more retransmissions take place, it becomes more likely that the problem is a decrease in the link quality. Therefore, at some point, the transmitting PRU will want to start transmitting the retransmissions at higher and higher power levels.

Taken together, these few simple modifications to existing PRNET algorithms would support power control within existing PRNET protocols. Therefore, minimum-hop routing could be performed with power control.

4. PREVIOUS SPATIAL REUSE ANALYSES

4.1 Overview of Previous Spatial Reuse Analyses

As discussed in Section 1.4, spatial reuse is the separation of PRUs in space such that some PRUs may transmit at the same time without destructively interfering with each other. The previous spatial reuse analytical work tried to optimize either the access protocol or the network topology and routing [Klein87].

Several papers examining the maximum optimal spatial reuse of networks have been published. Nelson and Kleinrock examined random and regular network topologies and showed that the maximum probability of transmission will be upper bounded by 0.9278/N where N is the network degree, i.e., average number of neighbors per PRU [Nelso83]. Silvester derived an algorithm to determine the optimal channel scheduling [Silve82]; and Nelson and Kleinrock developed an optimal TDMA protocol, called spatial TDMA, that assigned TDMA transmission rights to multiple PRUs during each time slot in a manner to provide for the greatest possible spatial reuse without interference [Nelso85].

4.2 Optimizing Spatial Reuse Through Power Control

The remainder of the previous analytic studies examined how to best modify the network topology through power control to improve spatial reuse. This analysis examined the following question first raised by Kleinrock, "Is it better for a route to take many short hops, or a few long ones?" [Klein75] If a small range is used, many hops are needed but there is little contention for the channel in each hop because only a few other PRUs will be within transmission range of the receiver. If a long range is used, only a few long hops are necessary, but the transmission for each hop must contend with much more interference.

4.2.1 Spatial Reuse in Regular Networks

Kleinrock's original paper indicated that there was an optimal range that should be used to minimize delay for a network with a continuum of nodes and the ability to arbitrarily adjust communications range (power). If the range is shorter, the number of hops will grow to infinity. If the range is longer, each transmission must contend with much more traffic and the throughput is decreased.

Akavia and Kleinrock [Akavi79] and Silvester and Kleinrock [Silve83a] [Silve80] examined regular topologies, such as rings and Manhattan grids. The basic results once again indicated that (as expected) the optimal transmission probability to maximize slotted Aloha performance is $p \cong 1/d$, where d is the average degree. They also found that the total network throughput for many types of networks, such as the Manhattan grid, is proportional to the square root of the number of nodes in the network.

4.2.2 Spatial Reuse in Random Networks

Of more interest to this dissertation is the previous research of spatial reuse in random networks. This work determined the optimal transmission ranges (or average degree) that would optimize network performance. This work has progressed through several refinements of the model and routing/transmission strategy since the original work by Silvester and Kleinrock [Silve80] [Klein78].

The basic model assumes that the channel access protocol is slotted Aloha with fixed length packets equal to the time slot, i.e., the radio propagation time is assumed to be zero. The PRUs are assumed to be distributed in a plane as a Poisson process. The traffic is assumed to be homogeneous and each node is ready to transmit with probability p in any slot (heavy traffic model). It is assumed that omni-directional antennas are used, so that rf signals propagate out equally in a circle in a plane. The threshold hearing model is used to simulate the rf channel and power propagation loss. Narrow-band channel signaling is assumed to be used with zero capture. Therefore, if two transmissions overlap at a PRU during a single time slot and that PRU is within the threshold distance of both transmitting PRUs, then the two packets are destroyed (interfered with) with probability 1. It is also assumed that all nodes transmit with the same range and that this range can be adjusted with infinite precision to optimize the network performance.

The analysis included a study of the myopic operation of several different routing/transmission strategies to find the single hop throughput, and then normalized the result to find the appropriate end-to-end throughput.

Ogier has developed a concise comparison between myopic and shortest path routing algorithms. Myopic schemes are based on forward progress, optimize only the next hop, and require knowledge of the destination's direction and neighbor's positions. Shortest path schemes use a link metric based on local information, optimize over all possible paths, and do not require position data, but do require the cost, i.e., distance, to each neighbor. Therefore, any shortest path scheme with metric m(i,j) can be converted to a myopic scheme by having PRU-i choose the PRU-j that maximizes forward progress divided by m(i,j) [Ogier87].

Basically, the analytic approach was to compute the expected progress toward the destination for an arbitrary transmission, as shown in Figure 4-1, where PRU-T transmits a packet to PRU-N on its way to the final destination PRU-D. The forward progress L of a successful transmission toward the destination is defined to be:

$$L = (X - X')$$

The progress term (X - X') varies depending on the routing/transmission strategy used and on the assumption made concerning what to do about PRUs that are either disconnected or else have no neighbors in the forward direction that can relay the packet toward the destination. In general, if we assume that the destination, PRU-D, is a far distance away, then W is a good approximation of the forward progress L.

The probability of success, s, of a single transmission is:

$$s = p\ (1 - p)\ e^{-pd}\ (1 - e^{-d})$$

where,

(1) p = the probability that the source PRU, PRU-T, transmits

(2) $(1 - p)$ = the probability that the relay PRU, PRU-N, is not transmitting

(3) e^{-pd} = the probability of no interference from other PRUs around PRU-N

(4) $(1 - e^{-d})$ = the probability of finding a PRU-N in the forward direction to the final destination, PRU-D

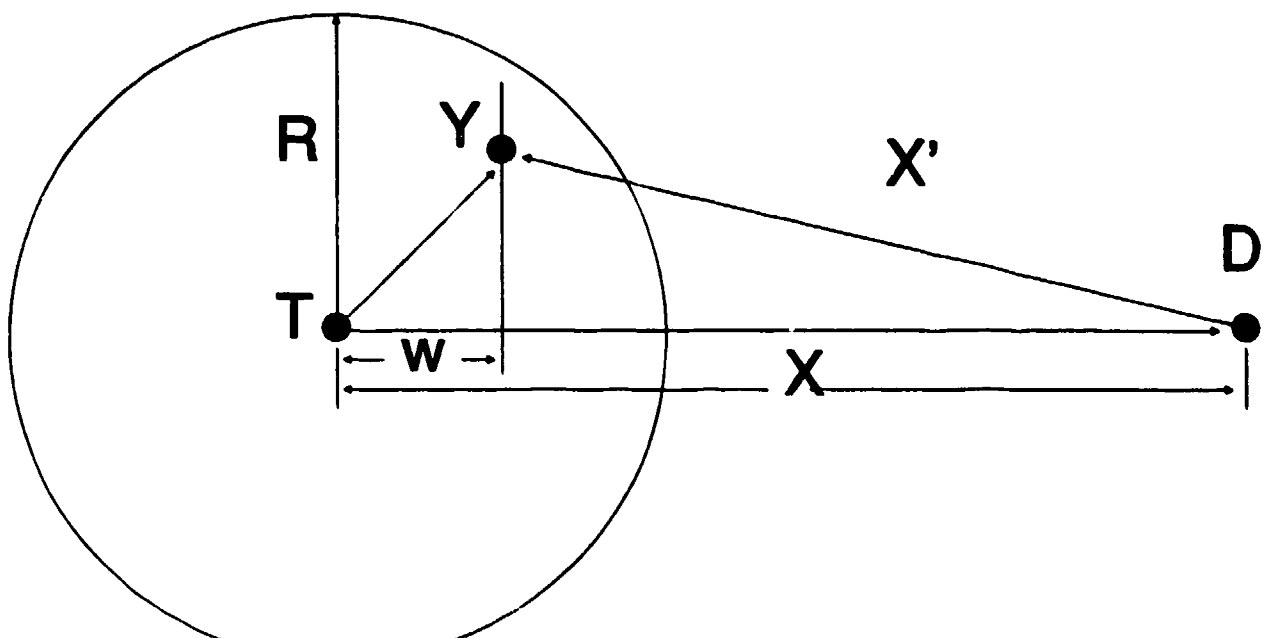


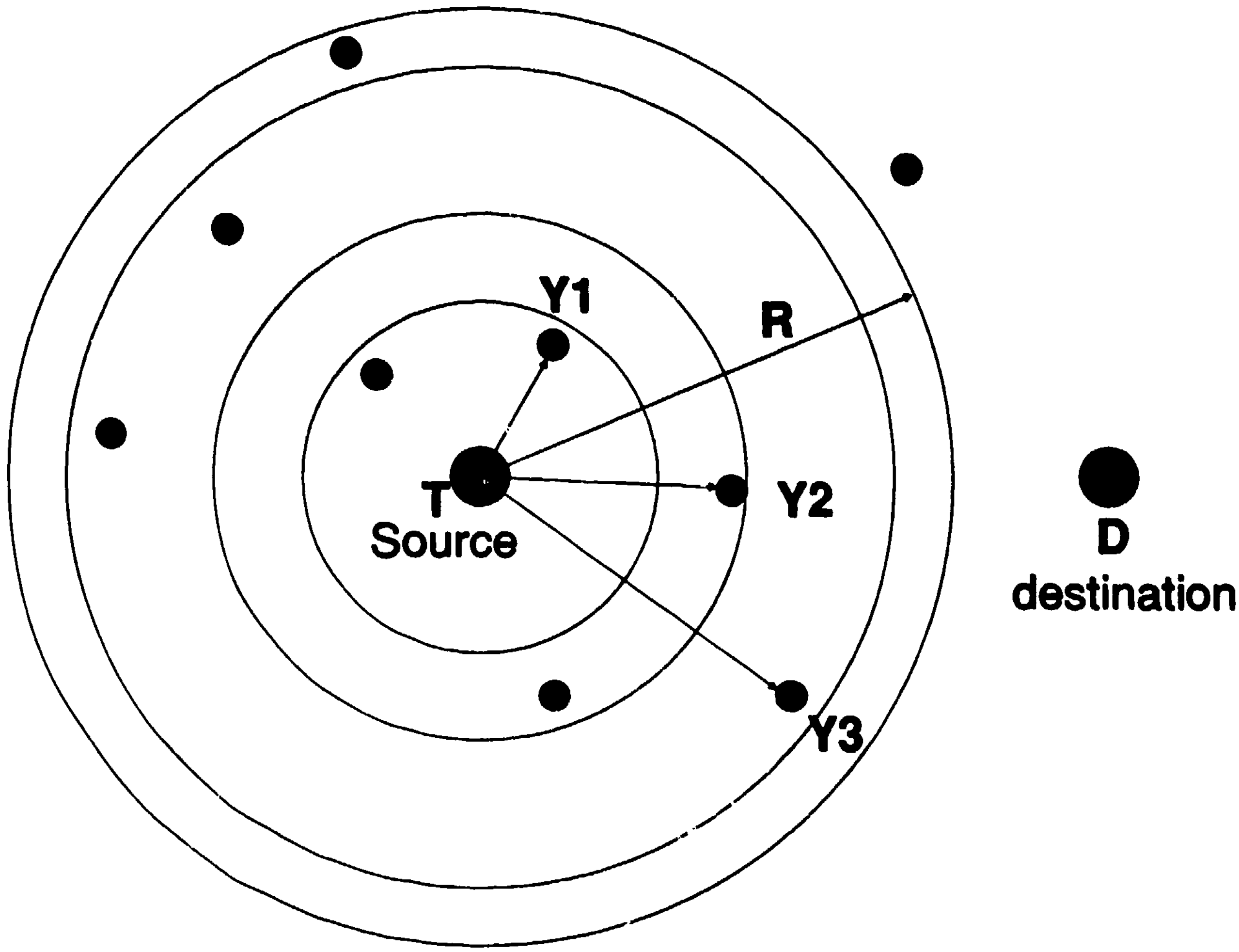
Figure 4-1. Forward Progress in a Random PRNET

The optimal transmission probability, p, is about 1/(d + 1), where (d + 1) accounts for the interference the source node causes to itself when it transmits. The expected forward progress, z, of an arbitrary transmission is:

$$z = L \bullet s$$

Several myopic routing/transmission strategies have been examined, including: Most Forward with Fixed Range (MFR), Nearest with Forward Progress (NFP), Most Forward with Variable Radius (MVR), and Least Area Routing (LAR). Figure 4-2 shows a comparison of the transmission strategies. Throughput simulation curves for these myopic strategies are shown in Chapter 6, where they are compared to the performance of a myopic version of LIR, presented in Chapter 5.

MFR is a myopic version of minimum-hop routing without power control, i.e., similar to what is implemented in most of today's multiple-hop operational PRNETs. In MFR, the packet is sent to the PRU-N within the fixed transmission range which maximizes the forward progress. MFR has been analyzed using several slightly different geometrical simplifications and either allowing or not allowing backward progress. Kleinrock and Silvester [Klein78] [Silve80] found that the optimal transmission range should be that which results in an average degree of 5.89 (or about 6). They also discovered that the performance is fairly insensitive to using a larger value, but very sensitive to using a smaller value, which increases the chances of not finding a PRU in the forward direction. Takagi and Kleinrock improved the model and found that the optimal average degree should be about 8 [Takag84]. Hou and Li performed a more precise



STRATEGY	TRANSMISSION RANGE	NEXT PRU
MFR	R	Y3
MVR	Distance between T and Y3	Y3
NFP	Distance between T and Y1	Y1
LAR	Distance between T and Y2	Y2

Figure 4-2. Comparison of Previous Myopic Transmission Strategies

geometrical analysis and found that an average degree of about 6 provides optimal PRNET performance [Hou86] [Hou85a] [Hou84].

Hou and Li introduced MVR, which is a myopic version of minimum-hop routing with power control. MVR is similar to MFR except that once the repeater PRU has been found, the source PRU adjusts its transmission range to just that needed to reach the repeater PRU [Hou86] [Hou85a] [Hou84]. MVR was shown to improve PRNET performance over MFR.

Hou and Li also introduced NFP, which is not similar to any operational PRNET routing metric.* NFP chooses the closest PRU in the forward direction and adjusts the transmission range to just that needed to reach the chosen PRU. NFP was shown to improve PRNET performance over MFR and MVR [Hou86] [Hou85a] [Hou84].

Hajek used a measure other than forward progress to study the network performance. This measure is called "efficiency" and is defined to be the expected progress divided by the area covered by the transmission. In general, the efficiency will provide the best progress at the least interference cost, because the expected interference is proportional to the area of transmission. He found that the optimal value for the average degree is about 3. If there is no PRU in the forward direction at that small a degree, then the transmission range is increased until a PRU is found in the forward direction. We will call his myopic routing strategy Least Area Routing

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* The closest proposed routing metric for an operational PRNET is the routing metric proposed for MSS, which is a function of transmit power, congestion and delay, and satellite battery power [Qualc87].

(LAR). Hajek showed that LAR improves PRNET performance over MFR, MVR, and NFP [Hajek83].

Chang and Chang modified the model to include the use of directional antennas instead of omni-directional antennas. The network performance was improved as expected, because the use of directional antennas eliminates much of the interference [Chang84].

Takagi and Kleinrock modified the model to use CSMA instead of slotted Aloha. The network performance using CSMA and MFR routing was improved, but only slightly (16%) because of the hidden terminal problem [Takag84].

Takagi and Kleinrock modified the model to include capture. The network performance using MFR routing was improved by 36 percent for a similar optimal average degree [Takag84]. Hou and Li also examined capture with the MFR and a more realistic channel model, and discovered that capture improves performance through the reduction of interference [Hou85a] [Hou85c].

Hou and Li also relaxed the model to examine a more realistic channel model, i.e., other than the threshold hearing model. They compared the original MFR and NFP along with two variants, M-MFR and M-NFP, which took the probabilistic hearing model in account; and found that the M-NFP provided better performance than NFP, MFR, or M-MFR. They also found that the more realistic channel model reduced the maximum possible normalized end-to-end throughput due to the additional interferences [Hou85b] [Hou85a].

Sousa and Silvester diverged from the previous work to examine spatial reuse in spread spectrum systems [Sousa85]. Their propagation model determined the interference contribution at a receiver from every other transmitting PRU in the network. This model took into account the attenuation of signal with distance as a function of some power law, e.g., the Free Space Law is a square law and the Plane Earth Law is a fourth power law. Knowing the interference at a PRU along with the signal strength from the transmitted packet (from the same propagation model) allowed them to determine the probability that the s/n ratio was above the threshold required for successful reception and, hence, the probability of a successful transmission. The optimization is no longer "what transmit range should I use" but rather "toward which PRU should I direct my transmission." They found that for a spread spectrum system, the optimal strategy is to address the packet such that there are 1.3 $\sqrt{K}$ PRUs between the transmitter and the addressed repeater PRU, where K is the multiuser capability of spread spectrum systems [Pursl87].

4.3 Problems with Myopic Strategies

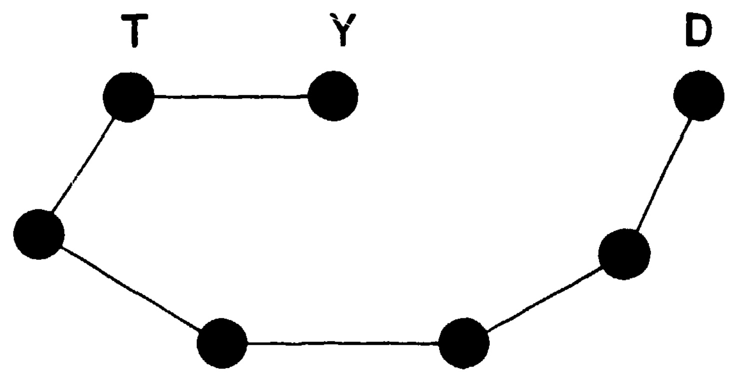
The existing analytic routing/transmission strategies have shown the importance of power control in providing spatial reuse and increasing the performance of the common-channel. Unfortunately, these myopic strategies, although useful for analysis, are not implementable in real operational networks.

Because the myopic strategies are performing a purely local routing decision, it is possible that they will choose a local optimal choice that will result in being unable to ultimately forward packets on to the destination even though a physical route really exists. For example, Figure 4-3A shows an example PRNET in which the MFR, MVR, NFP, and LAR strategies fail because PRU-T will always choose PRU-Y to try to route toward PRU-D even though a physical route exists from PRU-T to PRU-D. Figure 4-3B shows an example in which NFP and LAR will cause looping between two PRUs rather than ultimately routing a packet on to its intended destination.

These transmission strategies depended upon geographic information which often is not known in real operational PRNETs. Hou proposed that the PRUs could obtain this information from the Global Positional Satellite (GPS) system [Hou85d] [Hou85a]. Unfortunately, problems still exist even if this information is known because the variable nature of the rf channel as presented in Section 2.2.1.2. A PRU could require more power to reach the closest PRU in the forward direction than it does to reach the farthest PRU in the forward direction. This example could easily occur if the closest PRU were in a gully and the farthest PRU were on top of a hill. Therefore, the NFP interference assumptions would be violated if NFP chooses the closest PRU.

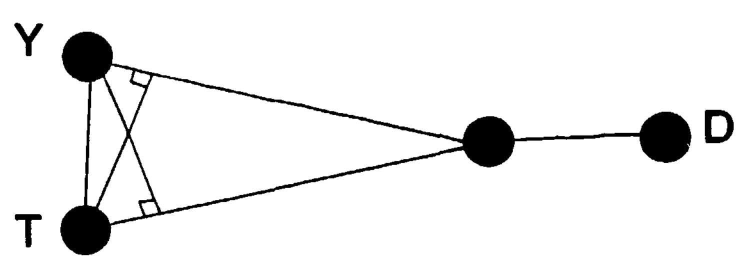
4.4 Conclusions

Although these myopic routing/transmission strategies cannot be implemented in real operational systems, their analysis does point out several important design ideas. In particular, the analyses indicate that network performance can be improved through spatial reuse from power control.



Step	MFR, MVR, NFP, & LAR Actions
1	PRU-T generates a packet destined for PRU-D.
2	PRU-T forwards packet to PRU-Y
3	PRU-Y discards packet since it cannot forward it on.

A. Dead-end Route Problem



Step	NFP, & LAR Actions
1	PRU-T generates a packet destined for PRU-D.
2	PRU-T forwards packet to PRU-Y
3	PRU-Y forwards packet to PRU-T
4 +	A loop of steps 2 & 3 ensues

B. Packet Looping Problem

Figure 4-3. Problems With Myopic Transmission Strategies

As interference is reduced, either through capture effects or directional antennas (and also through spread spectrum), the analyses indicate that the routes chosen by best routing strategies begin to converge to those chosen by MVR. This implies that designing a routing protocol which directly tries to minimize interference is more useful for narrow-band systems than for wide-band systems.

5. LEAST INTERFERENCE ROUTING

5.1 Least Interference Routing Overview

This chapter discusses a new routing protocol called Least Interference Routing (LIR). The LIR protocol has been designed to be an operational protocol in which each PRU is allowed to make a decision on what per-packet transmit power level to use and what PRU to select as the next PRU on the route to the final destination.

Notice that a myopic version of LIR would be to optimize the forward progress divided by the number of potential interferences caused. Therefore, LIR is similar to Hajek's transmission strategy LAR.* However, LIR should have better performance than LAR because LIR tries to minimize the actual interference instead of the area covered by the transmission, which is an average measure of interference.

The LIR protocol is composed of three operations:

(1) a local calculation of the potential destructive interferences across each link,

(2) the use of the potential destructive interferences as the routing metric to be minimized in a shortest path routing algorithm, and

(3) the specification of the per-packet transmission strategy at each PRU.

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* Hajek said that "It would be interesting (and it appears difficult) to find a dynamic transmission radius rule which minimizes [sic, should be maximizes] the mean forward progress divided by the mean number of stations in transmission range, other than the intended receiver." [Hajek83] Notice that Chapter 6 will show that this is exactly the myopic version of narrow-band LIR.

LIR allows great flexibility in how to perform each operation, thus allowing implementation in a variety of radios and radio networks.

5.2 Calculating the Potential Interference For a Given Transmission

As discussed in Section 2.2.1.6, the potential interference is dependent on the probability that two rf signals overlap, as well as on the conditional probability that the two rf signals interfere with one another given that they overlap. The probability that the two rf signals overlap in time at a PRU is a function of the channel access scheme used. At one extreme in common-channel random-access PRNETs is Aloha, and at the other extreme is CSMA in a single-hop PRNET. Although CSMA greatly reduces the probability of overlap over Aloha in single-hop networks, it provides a much smaller improvement for multiple-hop networks because of the hidden neighbor problem [Tobag74]. Because most of the operational PRNETs are multiple-hop, we will assume that the overlap probability is fairly constant and not consider it further.*

The potential interference that a PRU-i transmission causes to another PRU's (PRU-j) transmission, given that the two transmissions overlap in time at a third PRU (PRU-k) is dependent upon whether the channel signaling is narrow-band or wide-band and upon the amount of capture that the signaling provides. (Note that the potential interference for the special case of

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* The assumption that the overlap probability is fairly constant may be a bad assumption for networks using CSMA. For example, it may be a poor decision to adjust transmission range to just reach a PRU in a fully connected PRNET, and thus create hidden neighbors instead of transmitting at full power so that there are no hidden neighbors.

i = k is independent of the channel signalling, because we are assuming that each PRU has only a single antenna, transmitter, receiver, and modem and thus can either transmit or receive, but not both at the same time.)

At one extreme is a narrow-band system with zero capture. In this system, the potential interference calculation should include every PRU that could hear a transmission. At the other extreme is a wide-band system using transmitter-directed codes. In the wide-band system, only one PRU will be transmitting using that code, and therefore, the receive listening on the correct transmitting PRU code should have perfect capture. Thus, the potential interference calculation would only include the transmitting PRU and the receiving PRU.

Section 2.3.2 listed many different measurements that can be used to determine link quality. Similarly, there are many different ways to use these measurements to predict the potential interference across each link.

A very simple idea would be to consider the potential interference across a link to be either 1 or 0, based upon whether the quality of the rf link between PRU-i and PRU-k was considered good or bad. If the link quality were good from PRU-i to PRU-k, then the potential interference = 1; otherwise, the potential interference = 0. (Note that the potential interference for the special case of i = k is 1, because we are assuming that a PRU cannot transmit and receive at the same time.)

Figure 5-1 shows the example 10 node PRNET discussed in Section 3.4. If we assume the threshold hearing model and that the PRUs have the same maximum transmit power

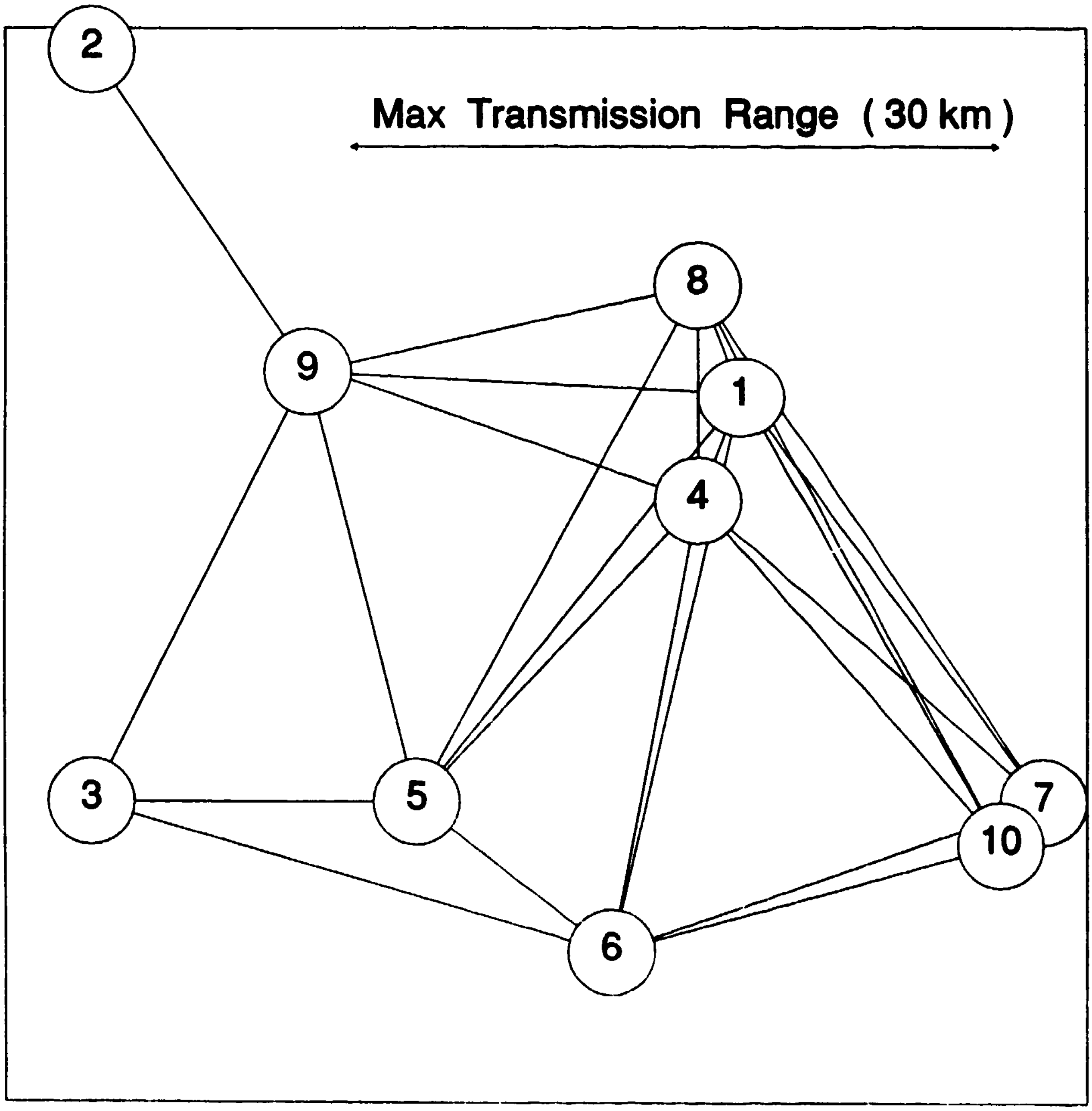


Figure 5-1. Example 10 Node Partially Connected PRNET

level as before, then Table 5-1 shows that the potential interference is reduced when PRU-10 transmits to each of its neighboring PRUs using both continuous and discrete dynamic power control.

A multi-valued link quality measurement could be used to calculate a multi-valued potential interference measurement. For example, the s/n ratio between PRU-i and PRU-k could be measured as part of the link quality measurement. If the s/n ratio is above one threshold, then the potential interference could be set equal to 1; if the s/n ratio is above another threshold, then the potential interference could be set equal to 1/2; else the potential interference could be set equal to 0.

Once a particular method of measuring the potential interference has been determined, then PRUs will use this method to calculate the potential interference to each PRU in the PRNET at different transmit power levels. Then, each individual potential interference can be summed to compute the total potential interference that a PRU causes when it transmits, as discussed in Section 2.2.1.6.

Note that operational PRUs do not have a continuum of possible transmission power levels. Instead, they usually have a few possible discrete transmission levels. Also, operational PRUs will leave an rf margin, of 3 dB, for example, to account for unpredictable changes in the environment. If a PRNET is operating in a line-of-sight (LOS) ground-based mode, then a PRU will typically need to have a dynamic transmission power range of about 40 to 45 dB to provide a transmission range of from 50 meters to 10 to 15 kilometers using the Free Space Law.

Neighbor PRU	Distance (km)	Potential Interference
1	24.19	6
4	21.26	6
6	18.97	6
7	2.83	6
8	29.53	6

A. Neighbor Table When Using a Constant Transmit Power

Neighbor PRU	Distance (km)	Attenuation (dB) from max power	Potential Interference
1	24.19	1.9	5
4	21.26	3.0	4
6	18.97	4.0	3
7	2.83	20.5	2
8	29.53	0.1	6

B. Neighbor Table When Using Continuous Dynamic Transmit Power Control

Neighbor PRU	Distance (km)	Good link at following (dB) attenuations from max power			
		0	3	9	27
1	24.19	Y	N	N	N
4	21.26	Y	Y	N	N
6	18.97	Y	Y	N	N
7	2.83	Y	Y	Y	N
8	29.53	Y	N	N	N

Attenuation (dB) from max power	Potential Interference
0	6
3	4
9	2
27	1

C. Neighbor Table When Using Discrete Dynamic Transmit Power Control

Table 5-1. PRU-10's Neighbor Tables for 10 Node PRNET in Figure 5-1

Any two PRUs that can correctly transmit and receive packets between each other will normally exchange link status packets to keep track of the status of their common rf channel (or link) Each PRU normally maintains this information in its Neighbor Table. The implementation of LIR means that PRUs will need to measure/predict the potential interference between themselves at different transmit powers, exchange this information in their link status packets, and store this information in their Neighbor Tables.

5.3 Calculating LIR Routes

Once the potential interference has been found at multiple power levels, then PRUs exchange interference measurements to calculate the least interference routes. The PRUs can use any shortest-path routing algorithm discussed in Section 2.4.

If the distributed incremental routing method is used, then the routing level update for any given PRU-i would be:

PRU-i routing level to PRU-i = 0

PRU-i routing level to every other PRU-m in network =
minimum for all neighbors k (
  neighbor PRU-k's routing level to PRU-m +
  amount of potential interference PRU-i causes when it transmits to PRU-k)

For example, Table 5-2 shows the LIR and Minimum-Hop routing tables for the 10 node PRNET in Figure 5-1. We see that the Minimum-Hop routes always have the same or greater interference than the LIR routes. The sum of the interference over all routes was 726 for Minimum-Hop and 657 for LIR, while the sum of the total hops over all routes was 134 for

Destination PRU	Potential Interference	Route
1	6	10-1
2	12	10-1, 1-9, 9-2
3	12	10-6, 6-3
4	4	10-4
5	12	10-1, 1-5
6	3	10-6
7	2	10-7
8	6	10-8
9	9	10-1, 1-9

A. Minimum Hop Routing Table

Destination PRU	Potential Interference	Route
1	6	10-1
2	11	10-4, 4-9, 9-2
3	12	10-6, 6-3
4	4	10-4
5	9	10-6, 6-5
6	3	10-6
7	2	10-7
8	6	10-8
9	8	10-4, 4-9

B. Least Interference Routing Table

Table 5-2. PRU-10's LIR-nap and MinHop-nap Routing Tables
for 10 Node PRNET in Figure 5-1

MinimumHop routing and 138 for LIR. (We will call these variants of LIR and Minimum-Hop routing "LIR-nap" and "MinHop-nap," respectively, to indicate that they use power control but do not have hop-by-hop acknowledgments.)

Note that LIR will not be an optimal routing algorithm. Such an optimal algorithm would have to take traffic patterns into consideration and would probably have to perform some sort of load splitting. Unfortunately, calculating the optimum routing solution to reduce the total network interference is difficult and requires a priori knowledge of the expected traffic load. Although LIR may not generate the optimal network routing solution, it is an important algorithm because of its ease of implementation and its embodiment of the concept of reducing interference to improve network performance through increased spatial reuse.

5.4 The LIR-Based Transmission Strategy

When a PRU has a packet that it intends to forward to a destination PRU, that PRU will look up the destination PRU in its Network Routing Table to determine the next PRU in the route to the destination. (Note that the forwarding PRU could be either the packet source PRU or a relay PRU on the route from the source PRU to the destination PRU.) Currently, PRUs look in their Neighbor Table to determine the transmission parameters to use. If the PRU can support dynamic power control, then the dynamic power control methods listed in Chapter 3 can be used. Otherwise, the PRU transmits the packets without power control.

5.5 LIR and Hop-by-Hop Acknowledgments

Because an rf channel has a noisy environment compared to wire-lines, PRNETs generally use some sort of hop-by-hop acknowledgment with hop-by-hop retransmissions to provide a high degree of probability that a packet will be received by the next PRU in a route, as discussed in Section 2.3.3.

If LIR were implemented as described earlier in this chapter, then passive acknowledgments could often fail when PRUs are relaying packets on to their destination PRUs. This failure occurs when the next PRU in a route transmits with a power level that is too low to be received at the previous PRU. Therefore, the next PRU should transmit with the minimum power required so that a packet can be received at both the next PRU in the route and at the previous PRU in the route. Figure 5-2A shows an example of this passive acknowledgment problem when a PRU in a sparse section transmits a packet to a destination PRU in a dense section of the PRNET. Using LIR as defined above, PRU-X transmits a packet to PRU-X and PRU-X transmits the packet to PRU-Y with a power level that is too small to reach back to PRU-T. Figure 5-2B shows the additional interference if PRU-T transmits an active acknowledgment back to PRU-T. Figure 5-2C shows the fewer additional interferences that result if PRU-X has to transmit with enough power (including margin) to support a passive acknowledgment back to PRU-T.

Note that, in special cases as shown in Figure 5-3A, when the PRU at the edge of the dense area has to transmit at a high power level for passive acknowledgments, there is a good chance that the destination PRU will receive the packet. However, it may still be advantageous

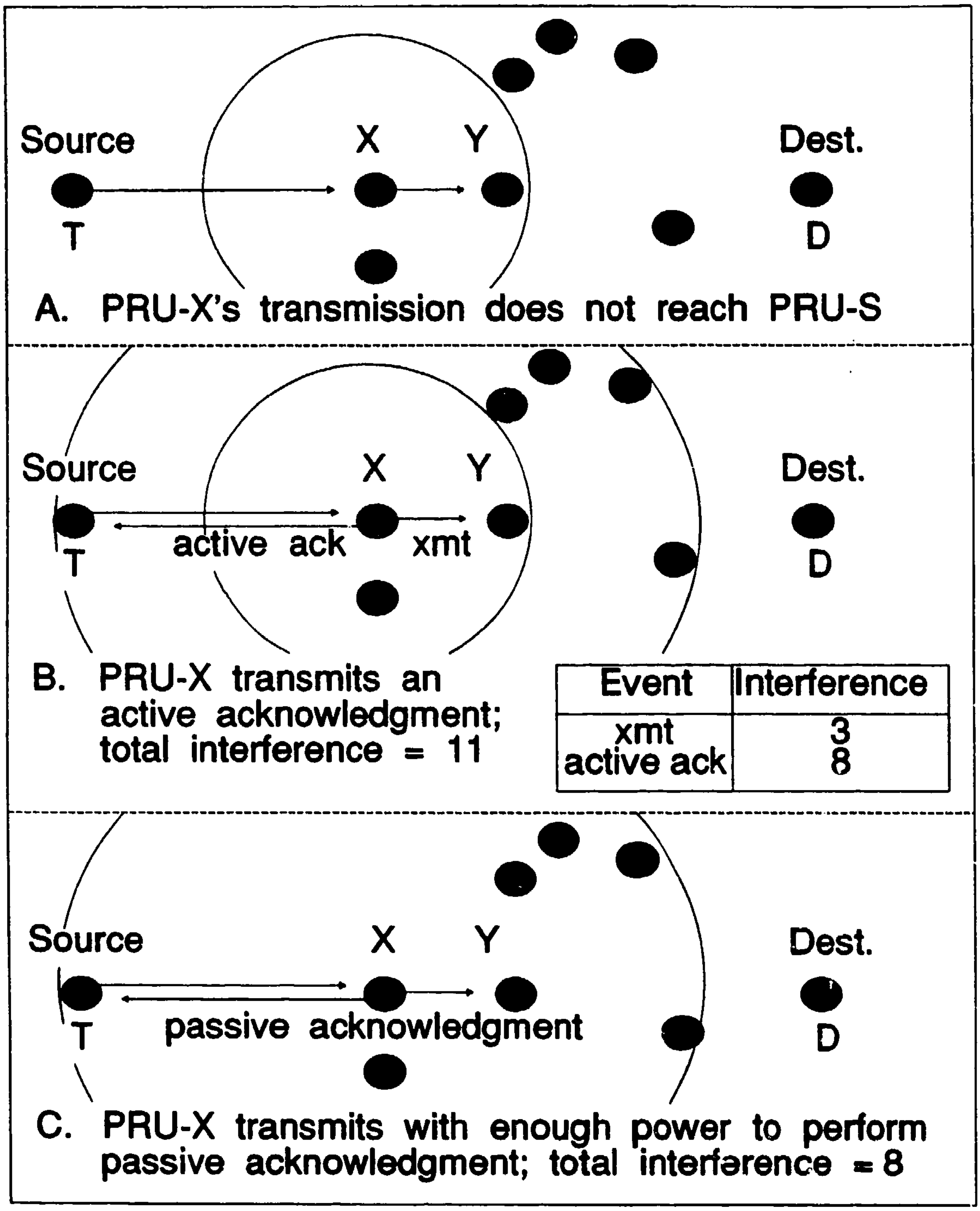


Figure 5-2. Including Passive Acknowledgments with LIR

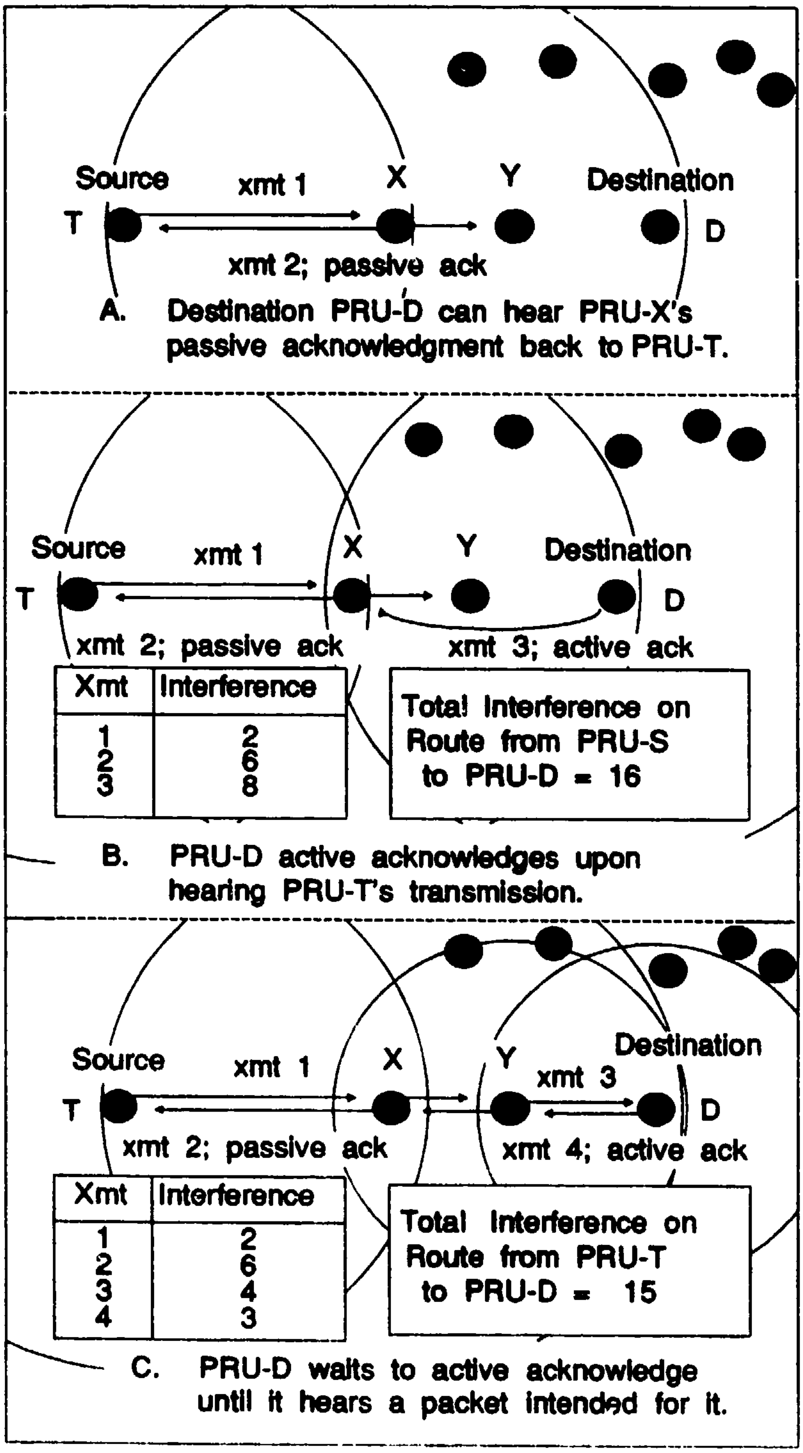


Figure 5-3. Including Destination PRU Active Acknowledgments with LIR

for the packet to be forwarded to the destination PRU using several small hops to reduce the total amount of PRNET performance degrading interference. For example, Figure 5-3B shows the number of potential PRNET performance degrading interferences when the destination immediately active acknowledges upon hearing a packet addressed to it, versus the smaller number shown in Figure 5-3C when the destination waits to active acknowledge until it receives a packet that is addressed to it as the next PRU.

The LIR protocol can be easily adapted to support passive acknowledgments by modifying the routing interference metric. If the distributed incremental method is used, the routing level update for any given PRU-i in the PRNET would be:

PRU-i routing level to PRU-i = 0

PRU-i routing level to every other PRU-m in network =
minimum for all neighbors k (
neighbor PRU-k's routing level to PRU-m +
potential interference when PRU-i transmits to PRU-k +
number of additional interferences, if any, that occur if PRU-k is a relay PRU and performs a passive acknowledgment or PRU-k is a destination PRU and performs an active acknowledgment)

For example, Table 5-3 shows the routing tables for this variant of LIR and Minimum-Hop routing for the 10 node PRNET in Figure 5-1. We see that the Minimum-Hop routes always have the same or more interference than the LIR routes. The sum of the interference over all routes was 1262 for Minimum-Hop and 1168 for LIR, while the sum of the total hops over all routes was 134 for Minimum-Hop routing and 140 for LIR. (We will call these variants of LIR and Minimum-Hop routing "LIR-ap" and "MinHop-ap," respectively, to indicate that they use power control and support hop-by-hop acknowledgments.)

Destination PRU	Potential Interference	Route
1	14	10-1
2	14	10-1, 1-9, 9-2
3	16	10-6, 6-3
4	11	10-4
5	18	10-1, 1-5
6	5	10-6
7	4	10-7
8	12	10-8
9	15	10-1, 1-9

A. Minimum Hop Routing Table

Destination PRU	Potential Interference	Route
1	14	10-1
2	13	10-4, 4-9, 9-2
3	16	10-6, 6-3
4	11	10-4
5	13	10-6, 6-5
6	5	10-6
7	4	10-7
8	12	10-8
9	13	10-4, 4-9

B. Least Interference Routing Table

Table 5-3. PRU-10's LIR-ap and MinHop-ap Routing Tables for 10 Node PRNET in Figure 5-1

Note that the distributed incremental method does not calculate the optimal routes for passive acknowledgments. Figure 5-4A shows an example route created using the routing level update listed above. Figure 5-4B shows that there are better routes to use to eliminate interference.

The optimum route shown in Figure 5-4B can be obtained by modifying LIR to exchange information about power levels with the routing tables. If a given PRU, say PRU-i, has N different power levels, then that PRU can logically be considered to be N different PRUs, and any shortest path routing algorithm can be used. We will call an actual PRU-i transmitting at the g^{th} transmit power level the logical PRU-i,g. If the distributed incremental method is used, then the routing level update for any given PRU-i in the PRNET would be:

PRU-i routing level to PRU-d =
minimum for all power levels g (PRU-i,g routing level to PRU-d)

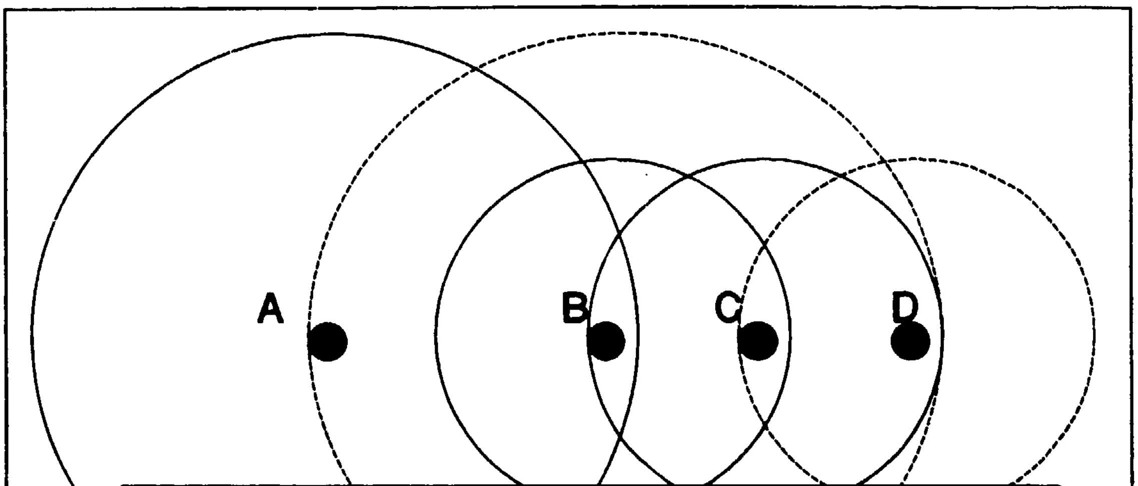
PRU-i,g routing level to PRU-i =
number of potential interferences when PRU-i transmits at the g^{th} power level

PRU-i,g routing level to every other PRU-m in network =
minimum for all neighbors k (
neighbor PRU-k,h's routing level to PRU-m (where power level h $\geq$ power level g) +
potential interference when PRU-i,g transmits to PRU-k,h)

Although we presume that the difference between the approximate calculation performed by the distributed incremental method and the calculation performed by the optimal distributed incremental method is small, we did not compute both routing types for comparison.

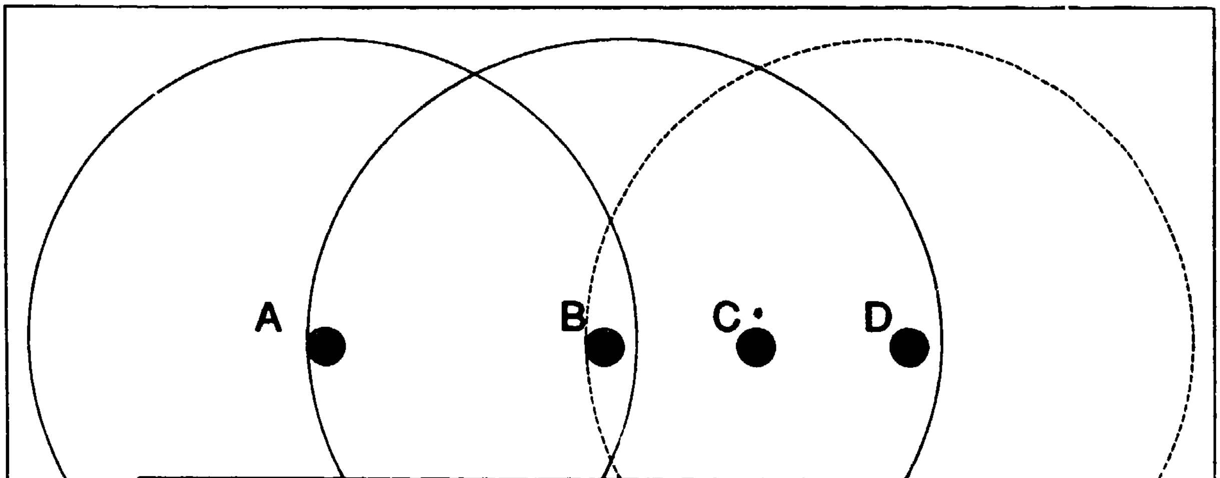
5.6 LIR and Networks Without Power Control

The LIR protocol has been designed to work in PRNETs containing PRUs that can



PRU-I	PRU-I's routing table entry to PRU-D				
	PRU-I LIR metric	next-PRU	next-PRU LIR metric	unaccounted acks interference; next-PRU back to PRU-I	interference from PRU-I to next-PRU
D	0	na	na	na	na
C	5	D	0	2	3
B	7	C	5	0	2
A	11	B	7	2	2

A. Approximate LIR Route With Acknowledgments



PRU-I	PRU-I's routing table entry to PRU-D				
	PRU-I LIR metric	next-PRU	next-PRU LIR metric	unaccounted acks interference; next-PRU back to PRU-I	interference from PRU-I to next-PRU
D	0	na	na	na	na
C	5	D	0	2	3
B	7	D	0	3	4
A	9	B	7	0	2

B. An Optimal LIR Route With Acknowledgments

Figure 5-4. Comparison of Approximate to Optimal LIR Routing with Acknowledgments change their transmit power levels on a packet-by-packet basis. However, LIR will still work for PRNETs with fixed transmit power levels. The only two changes to LIR are: (1) the potential destructive interference is measured at a single transmit power level instead of multiple levels, and (2) the LIR transmission strategy does not have to specify the transmit power level. In this case, LIR will route packets through the less dense PRNET areas, such as the edges.

In general, when there is no power control, the LIR routes are usually the same whether acknowledgments are considered or not. Therefore, we will only examine the variant of LIR without power control and without acknowledgments.

Table 5-4 shows the routing tables for this variant LIR and Minimum-Hop for the 10 node PRNET in Figure 5-1. We see that the Minimum-Hop routes always have the same or more interference than the LIR routes. The sum of the interference over all routes was 884 for Minimum-Hop and 852 for LIR, while the sum of the total hops over all routes was 134 for Minimum-Hop routing and 140 for LIR. (We will call these variants of LIR and Minimum-Hop routing "LIR-np" and "MinHop-np," respectively, to indicate that they do not use power control.)

5.7 LIR and Mobility

Note that LIR chooses PRUs that are generally closer than the PRUs chosen by minimum-hop routing, so that as neighbor PRUs move out of range, a PRU can just increase its rf transmit power to have a good chance of reaching its mobile neighbor PRUs. Therefore, the links used by LIR should be longer-lived than those used by Minimum-Hop routing and LIR should perform better than Minimum-Hop routing in mobile PRNETs.

Destination PRU	Potential Interference	Route
1	6	10-1
2	21	10-1, 1-9, 9-2
3	13	10-6, 6-3
4	6	10-4
5	14	10-1, 1-5
6	6	10-6
7	6	10-7
8	6	10-8
9	14	10-1, 1-9

A. Minimum Hop Routing Table

Destination PRU	Potential Interference	Route
1	6	10-1
2	20	10-1, 8-9, 9-2
3	13	10-6, 6-3
4	6	10-4
5	13	10-6, 6-5
6	6	10-6
7	6	10-7
8	6	10-8
9	13	10-8, 8-9

B. Least Interference Routing Table

Table 5-4. PRU-10's LIR-np and MinHop-np Routing Tables

for10 Node PRNET in Figure 5-1

5.8 LIR and Other Types of PRNETs

The examples have shown how LIR reduces interference over Minimum-Hop routing in narrow-band common-channel random-access PRNETs without capture. As other types of PRNETs reduce the interference caused by overlapping transmissions, i.e., through the use of capture, unique point-to-point channels, or contention-free channel access protocols, the routes chosen by LIR will begin to converge to those chosen by Minimum-Hop routing.

Therefore, although LIR will work in all PRNETs, not just common-channel random-access PRNETs, it may not make sense to implement LIR in all possible types of PRNETs.

5.9 LIR and Operational PRNETs

In general, a PRNET designer can use the following rules to determine which variant of LIR to use:

```
IF  the PRNET has multiple hop capability, i.e., performs routing,
    THEN IF  the PRNET does not have power control capability
             THEN  use LIR-np
             ELSE IF  the PRNET uses hop-by-hop acknowledgments
                      THEN  use LIR-ap
                      ELSE  use LIR-nap
    ELSE  {the PRNET has no need of LIR by definition}
```

By examining the list of operational PRNETs presented in Table 2-1, we see that LIR-ap could be implemented in the EPR/IPR DARPA PRNET, the LPR DARPA PRNET, the SINCGARS Packet Applique, and the RSRE CNR Packet Applique. Since the University of Hawaii Aloha PRNET and the Indoor PRNETs are single hop, LIR is not needed by definition.

Although LIR could be implemented in today's multiple-hop Amateur PRNETs, it is not recommended because the Amateur PRNET uses manual source routing.

In conclusion, the three operations that make up LIR have been described. The great flexibility on how to perform each of these operations allows LIR to be implemented in any multiple-hop PRNET. The fact that similar types of operations are performed in any multiple-hop operational PRNET means that LIR can be implemented without adding much more complexity to existing implementations.

6. MYOPIC SIMULATIONS OF LIR

6.1 Introduction

This chapter compares the performance of the myopic version of LIR to the myopic routing schemes presented in Chapter 4. For simplicity, we will only run simulations for narrow-band PRNETs without capture.

The myopic version of LIR chooses the PRU that maximizes forward progress divided by the amount of interference caused by the transmission. This means to choose the PRU that maximizes the forward progress divided by the number of PRUs within transmission range for narrow-band systems without capture.

Section 6.2 compares the performance of LIR with the previous myopic strategies for a PRNET using the threshold hearing model and a continuum of power level steps. Section 6.3 compares the performance for a PRNET with only a discrete number of power steps. Section 6.4 concludes the discussion of the simulation results.

6.2 The Basic Myopic Simulation

The basic myopic simulation will assume that a simulated PRNET is using narrow-band signaling and has zero capture. This means that if two PRU transmissions overlap in time at the same PRU, then they will destructively interfere with each other so that neither packet can be received correctly. In addition, the PRUs are assumed to be using slotted Aloha as the channel access protocol. The PRUs are located in the plane as a Poisson process. The basic simulation is an enhanced repeat of the analysis/simulation performed by Ogier who.simulated the myopic performance of LIR to many of the myopic strategies presented in Chapter 4 [Ogier87].*

Using the following notation:

L = forward progress

M = number of PRUs reached by a transmission, i.e., the potential interference caused by a transmission

R = distance from transmitter to receiver

R* = actual transmission radius

R" = fixed maximum transmission radius

N = number of PRUs in the PRNET

d = average degree, i.e., average number of neighbors per PRU

The myopic strategies may be written as follows:

MFR: maximize L, R* = R"

MVR: maximize L, R* = R

NFP: minimize R* such that L > 0, R* = R

LAR: maximize $L/\pi R^2$, R* = R

LIR: maximize L/M, R* = R

* Ogier is supported by the DARPA Survivable Adaptive Networks (SURAN) Program which also supported the LIR work. The concept of LIR and some examples of its operation were originally presented to the members of the SURAN program at its January 1987 Implementers Meeting by the author [Steve87]. LIR's simple solution to the previously difficult problem of spatial reuse and power control influenced the members of the SURAN working group to further work in this area. This related work is discussed in Chapter 8 in the section on ideas for future research.

We define a PRU's single hop throughput, s, as:

$$s = \text{(throughput of slotted Aloha in a single hop neighborhood)} \,/\, \text{(number of PRUs in the single hop neighborhood)} = 1/(M\,e) \qquad \text{[Silve80]}$$

Therefore, the total network single hop throughput, S, is:

$$S = N \bullet s = N/M\,e$$

Let z be the average expected progress, e.g., in miles, per slot from a transmitting node:

$$z = s \bullet L$$

Therefore, the total network expected progress, Z, is:

$$Z = N \bullet z = S \bullet L$$

Then $Z\sqrt{\lambda}$ is a normalized measure of average progress per slot, where λ is the average density of PRUs per unit area. $Z\sqrt{\lambda}$ is the normal measure of end-to-end throughput used in [Takag84] [Hou84] [Hou85a] [Hou85b] [Hou85c] [Hou86], and is equivalent to g, the end-to-end throughput measure used in [Silve80] [Silve83a] [Silve83b] [Klein78].

Note that, as discussed in [Hajek83], L/M is a local measure (independent of the PRNET's global geometry) that is proportional to the end-to-end throughput. Therefore, we will obtain L/M as well for comparison of the myopic schemes.

The simulation to compute the myopic throughput is as follows: 99 PRUs were uniformly distributed in a unit square along with a PRU (designated as the transmitter PRU) in the center of the square. Thus $\lambda = 100$.

The ired numbe. .. neighbors, d, was input and a fix transmit radius was chosen to yield the average number of neighbors. Remembering that:

$$N = \lambda \pi R''^2$$

for nodes distributed in the plane as a Poisson process, we can re-arrange the equation and substitute d for N and 100 for λ to get:

$$R'' = \sqrt{d / 100 \pi}$$

The x direction represents forward progress. If a PRU cannot be found in the forward direction within radius R", then we consider L, M, S, and $Z\sqrt{\lambda}$ to be zero for that run.

Thus, L, M, S, and $Z\sqrt{\lambda}$ were computed for each of the myopic schemes; 1000 runs were made and the results averaged to obtain the L, M, S, and $Z\sqrt{\lambda}$ for a single value of M. The simulation was then run for values of d between 2 and 25. Figure 6-1 shows a flow-chart of the simulation algorithm.

Figure 6-2 shows the average hop-by-hop throughput versus average number of neighbors for each of the myopic schemes. Figure 6-3 shows the average number of interferences that occur per average number of neighbors. Figure 6-4 shows L, the average single hop forward progress, for each myopic scheme versus the average number of neighbors. Figure 6-5 shows the average of L/R". Figure 6-6 shows the efficiency of each of the myopic schemes, and Figure 6-7 shows $Z\sqrt{\lambda}$, a measure of the end-to-end throughput.

Note that the simulation values of the myopic schemes agree fairly well with the published results in [Hou84] [Hou85a] [Hou86], except that: (1) our end-to-end throughput cur-

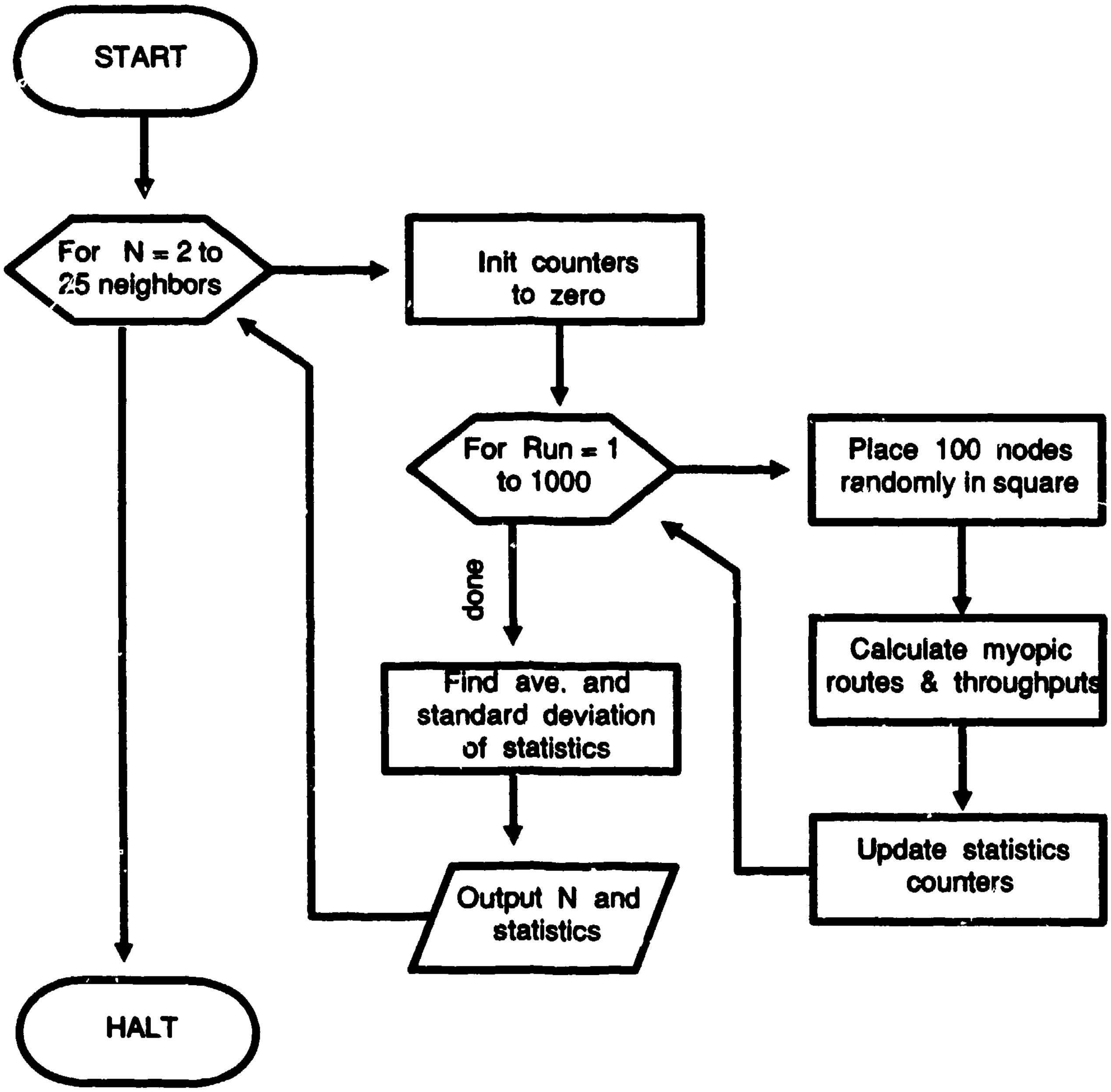


Figure 6-1. Basic Myopic Simulation Flowchart

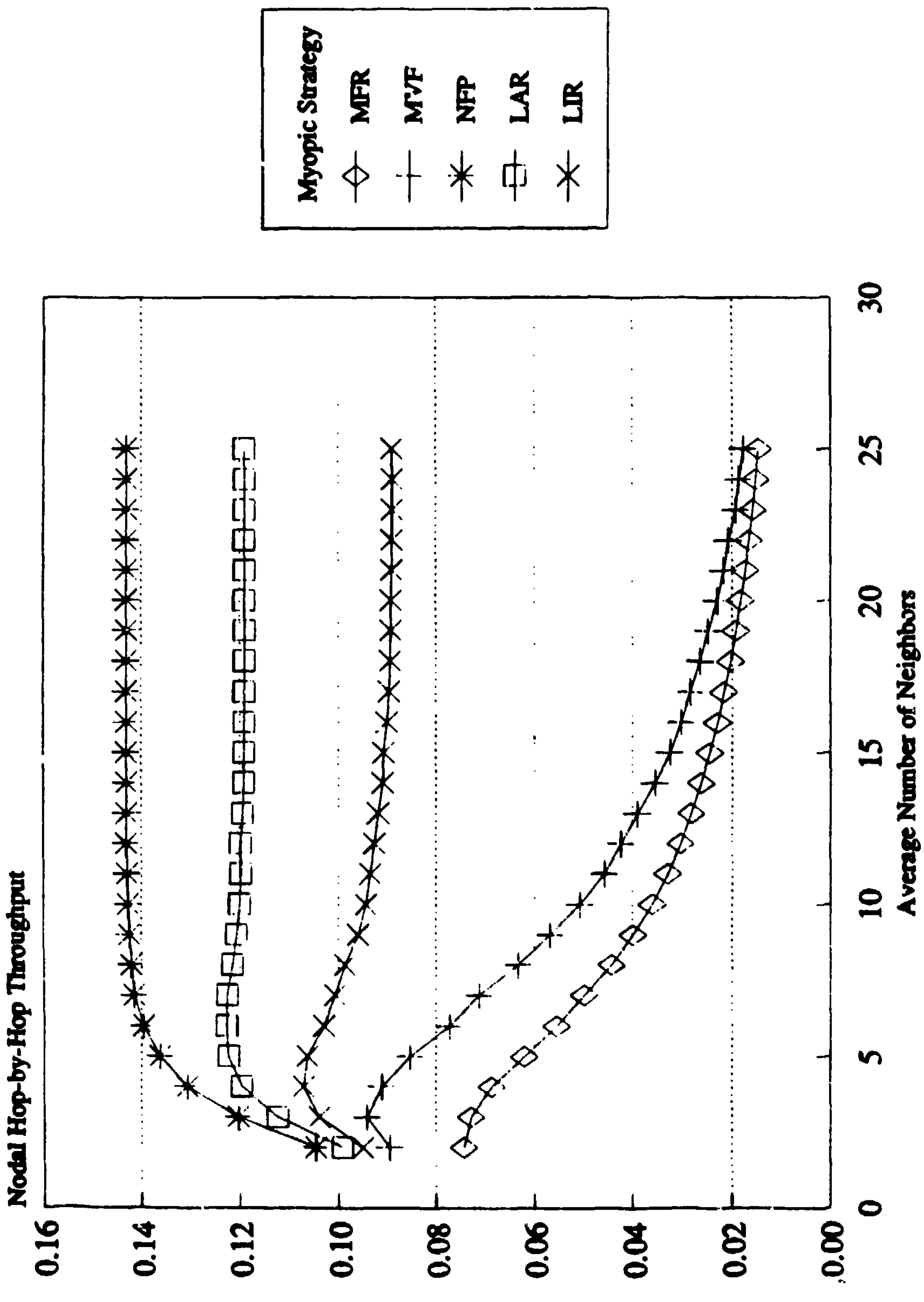


Figure 6-2. Hop-by-Hop Throughput

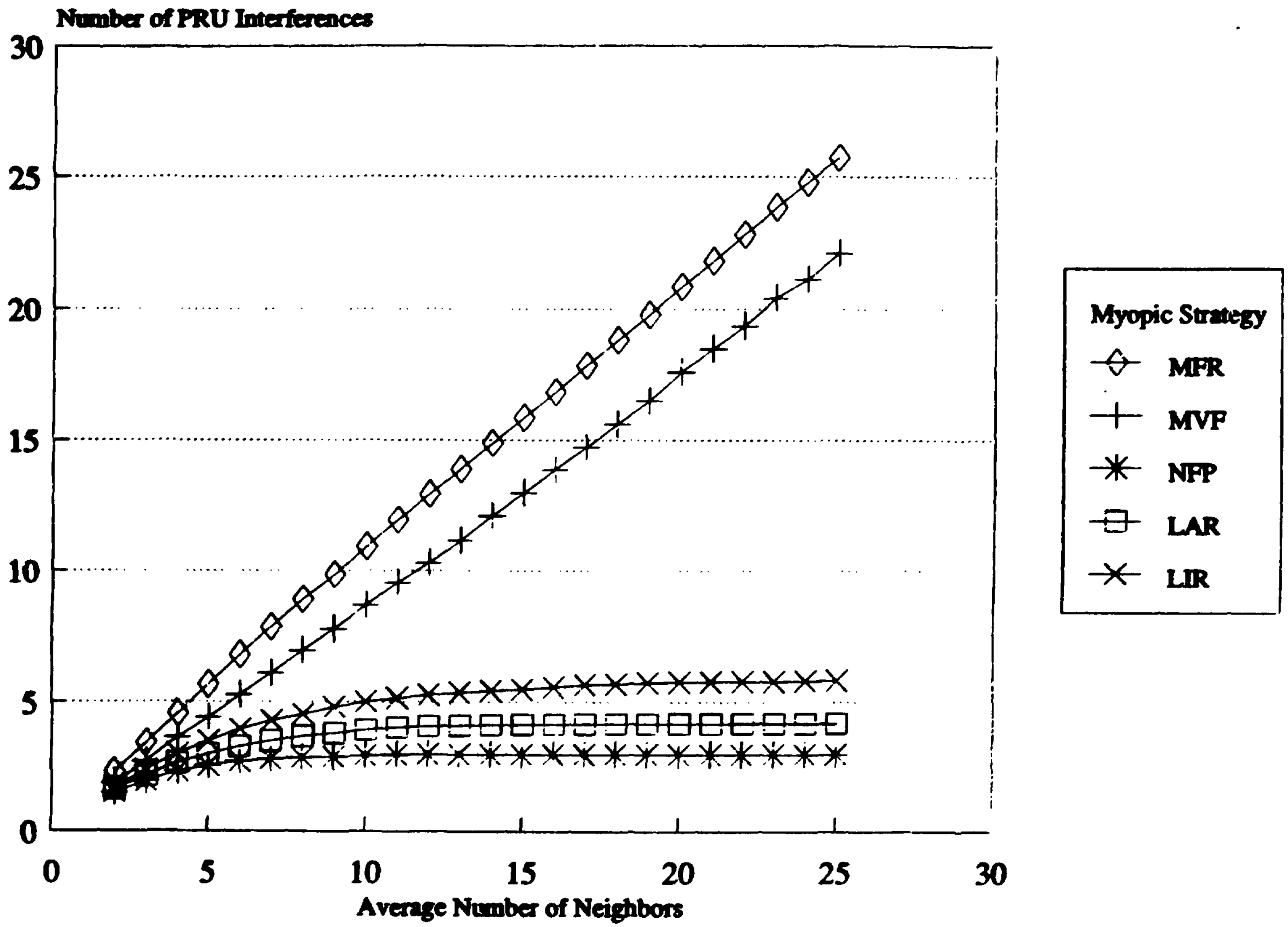


Figure 6-3. Interferences

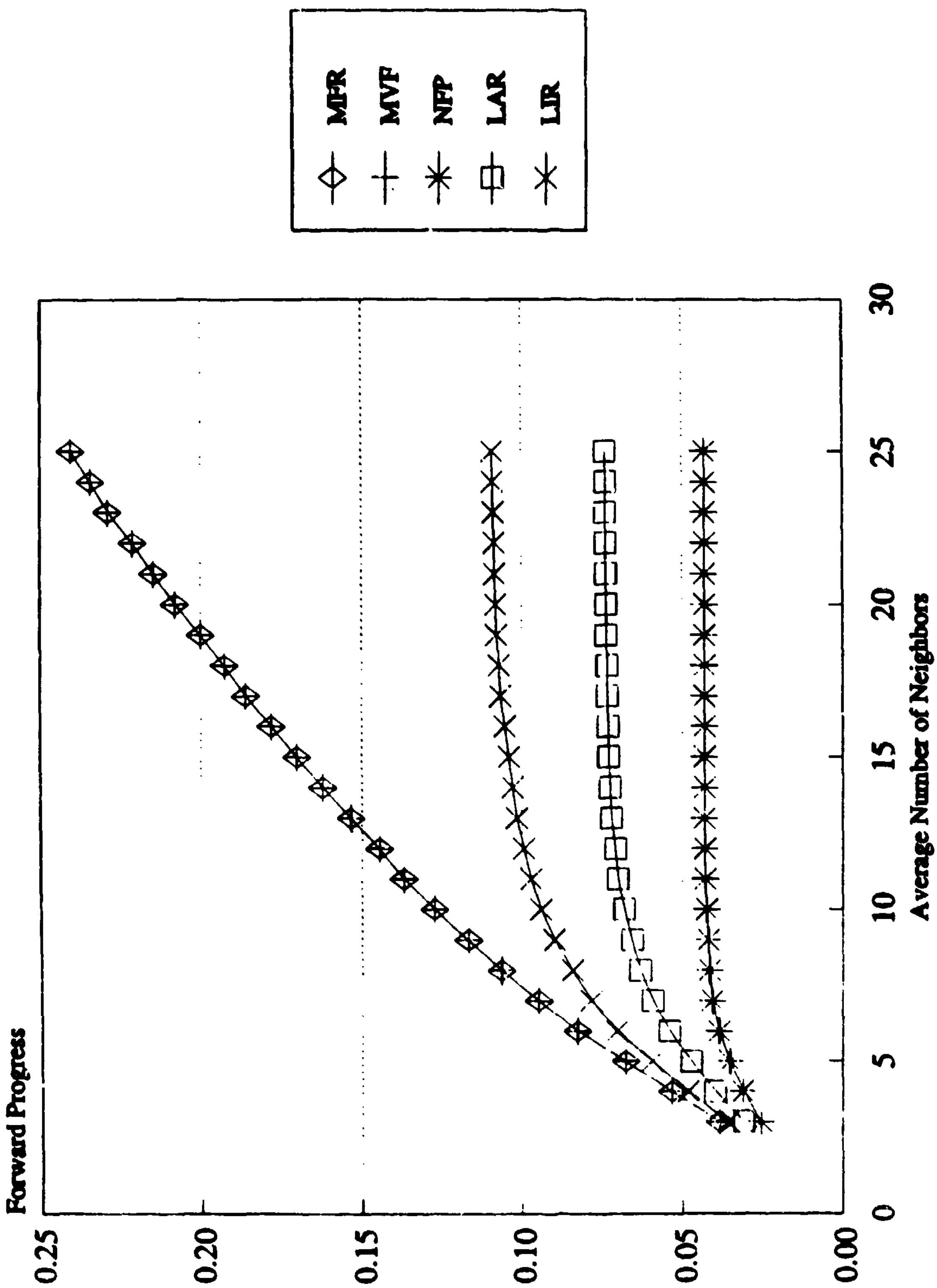


Figure 6-4. Average Single Hop Forward Progress

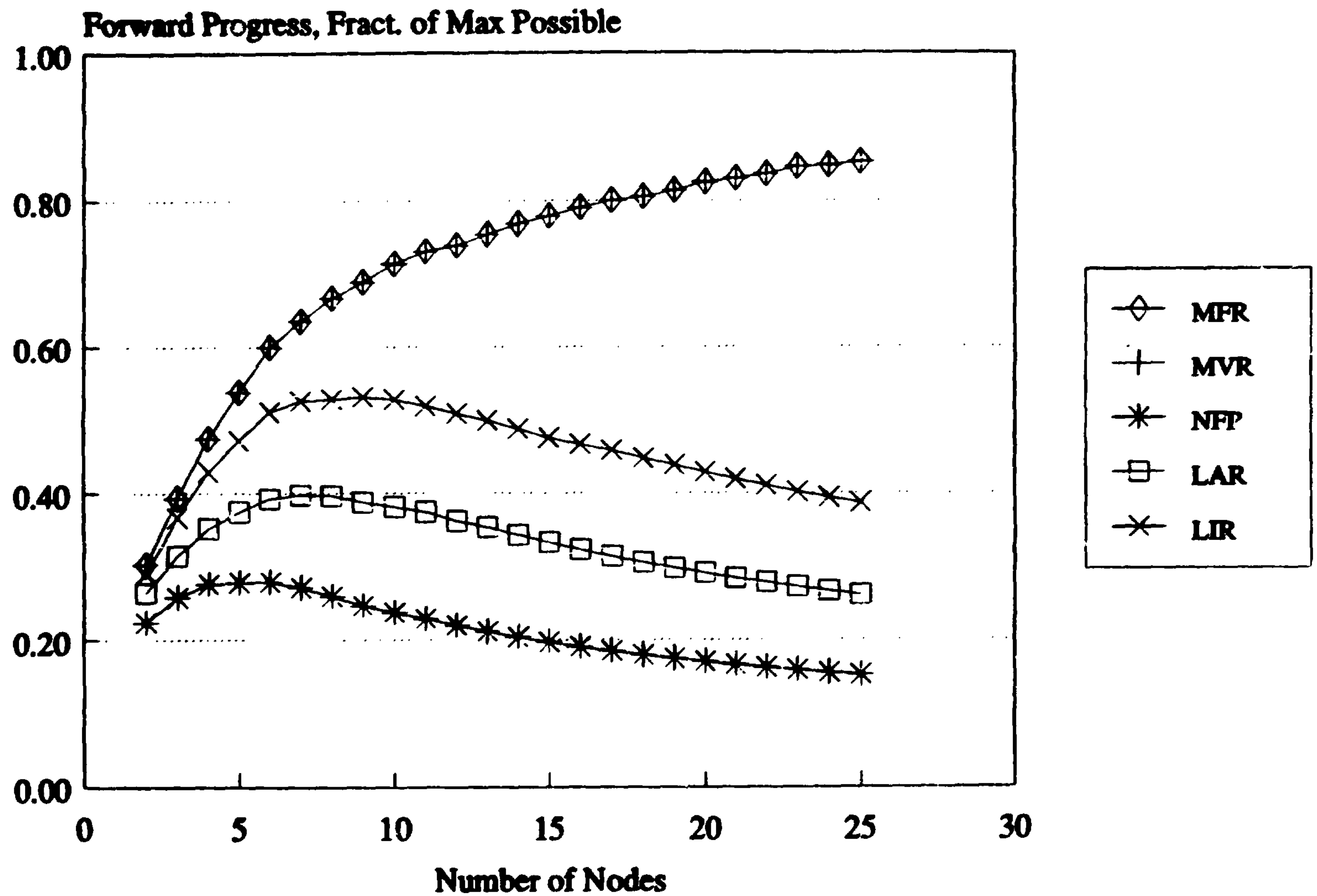


Figure 6-5. One Hop Progress as Percentage of Maximum Possible Progress

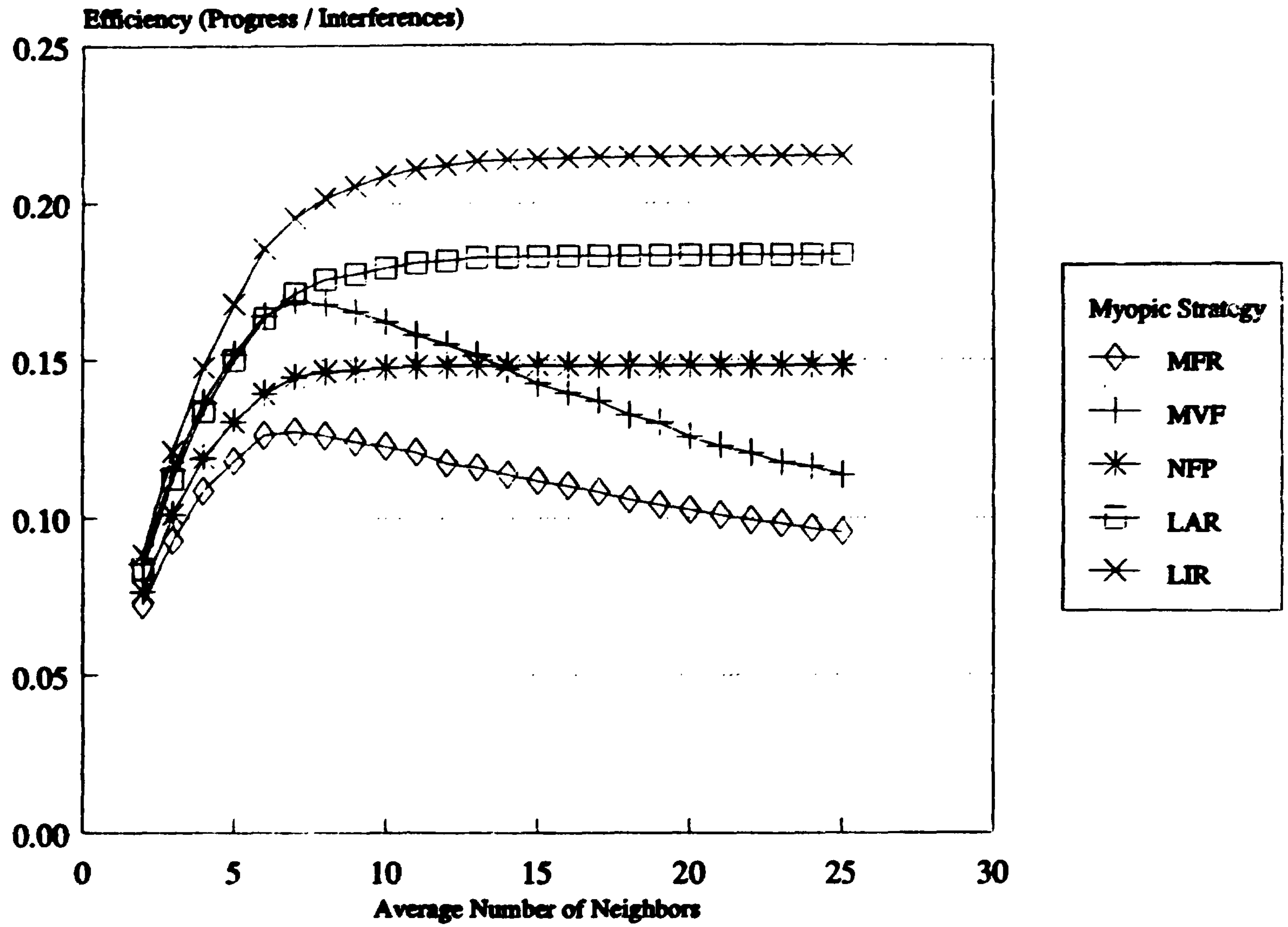


Figure 6-6. Progress / Interference

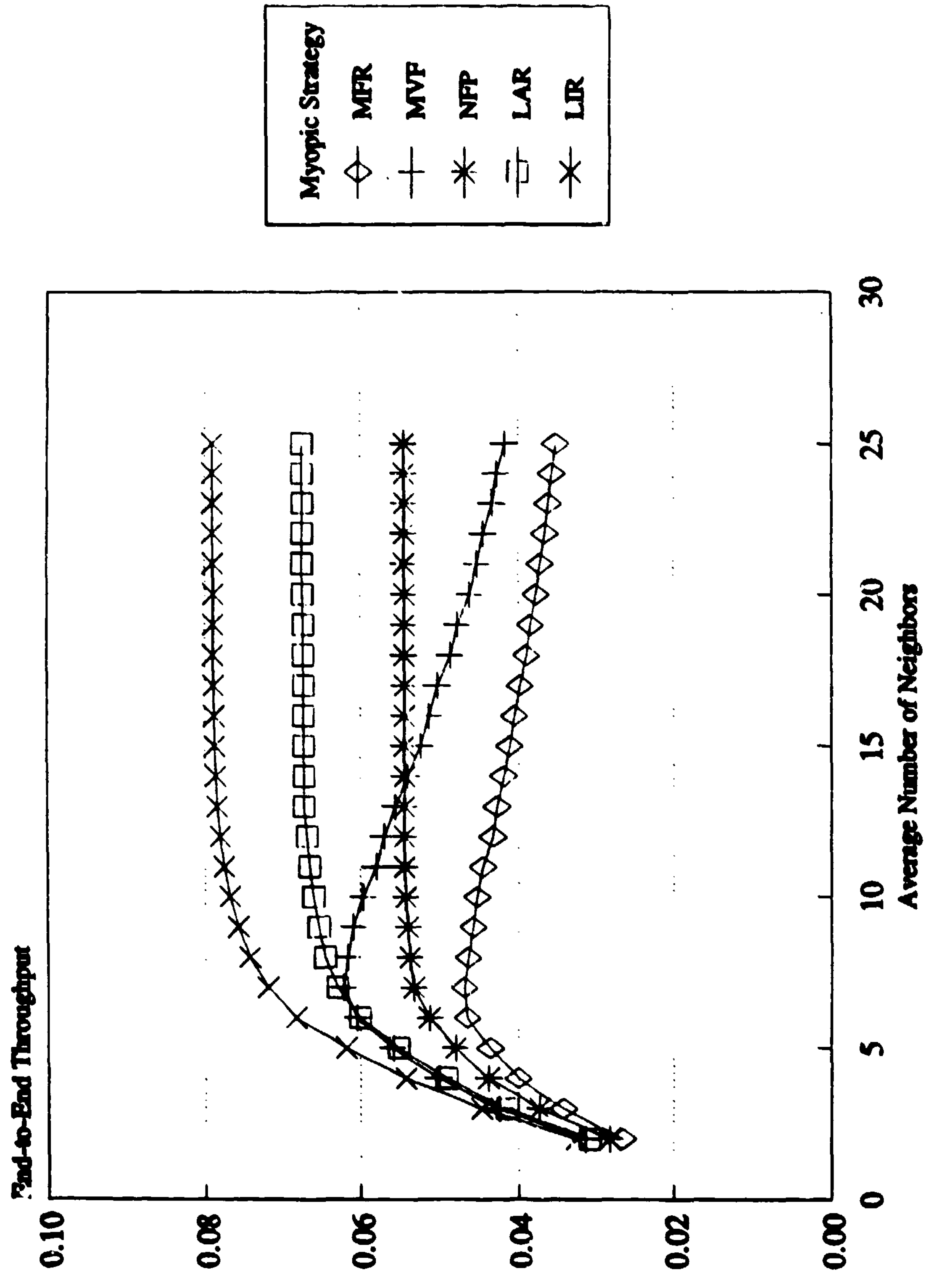


Figure 6-7. End-to-End Throughput

ves show a little better performance than in [Hou84] [Hou85a] [Hou86]; and that (2) our $Z\sqrt{\lambda}$ end-to-end throughput curve for NFP does not decrease slightly with increasing d for d >10, but instead remains level. We presume that this difference occurs due to the difference in how we calculate the forward progress. We followed the method of [Silve80] [Klein78] [Takag84] and neglected a slight negative correction to L, the forward progress, for simplicity. Our MFR throughput curve therefore corresponds very closely to the MFR curve in [Takag84].

The results show, as expected, that LIR provides the best myopic end-to-end performance. NFP shows better hop-by-hop performance but less end-to-end performance because each NFP hop covers a small range compared to an LIR hop. We note that the LIR end-to-end throughput is insensitive to changes in the average number of neighbors greater than about eight. Therefore, LIR would be a good algorithm to implement in dense PRNETs.

6.3 Extending The Basic Myopic Simulation To Include Discrete Power Steps

The basic myopic simulation from 6.2 was extended to include discrete power steps. We basically assumed that there was sufficient range control to cover 2 orders of magnitude, i.e., from 0.1 to 10 kilometers or from 1 to 100 kilometers. As shown in Section 2.2.1.2, this requires 40 dB for a Free Space Propagation Law and 80 dB for a Plane Earth Propagation Law. The discrete power steps are assumed to divide the dynamic power range up into even dB steps resulting in uneven changes to the transmission radius as shown in Figure 2-2.

We extended the notation from 6.2 to include discrete power steps:

P = number of discrete power steps; (P = 1, 2, 3, ...)

R' = fixed minimum possible range (note that if P=1, then R'=R")

$Rp(i) = R' + (R'' - R')(i-1)/P; \quad (1 \le i \le P)$

We then modified the myopic strategies as follows:

MFR: maximize L, R* = R" (unchanged)

MVR: maximize L,

$$R^* = \begin{cases} R' & \text{if } R \le R' \\ Rp(i) & \text{if } Rp(i-1) < R \le Rp(i) \end{cases}$$

NFP: minimize R* such that L > 0,

$$R^* = \begin{cases} R' & \text{if } R \le R' \\ Rp(i) & \text{if } Rp(i-1) < R \le Rp(i) \end{cases}$$

if there are two or more PRUs with L between R* and the previous Rp, then pick the PRU that will maximize L

LAR: maximize $L/\pi R^2$,

$$R^* = \begin{cases} R' & \text{if } R \le R' \\ Rp(i) & \text{if } Rp(i-1) < R \le Rp(i) \end{cases}$$

if there are two or more PRUs with L between R* and the previous Rp, then pick the PRU that will maximize L

LIR: maximize L/M,

$$R^* = \begin{cases} R' & \text{if } R \le R' \\ Rp(i) & \text{if } Rp(i-1) < R \le Rp(i) \end{cases}$$

if there are two or more PRUs with L between R* and the previous Rp, then pick the PRU that will maximize L

Figure 6-8 is a flowchart of the extended simulation. Figure 6-9 shows the $Z\sqrt{\lambda}$ end-to-end throughput versus the average number of neighbors for different numbers of power steps for MFR. Figures 6-10 through 6-13 show the similar graphs for MVR, NFP, LAR, and LIR, respectively. As expected, the MFR graph shows no difference with the number of power steps because it always uses the maximum possible power step. Note that, although MVR and NFP

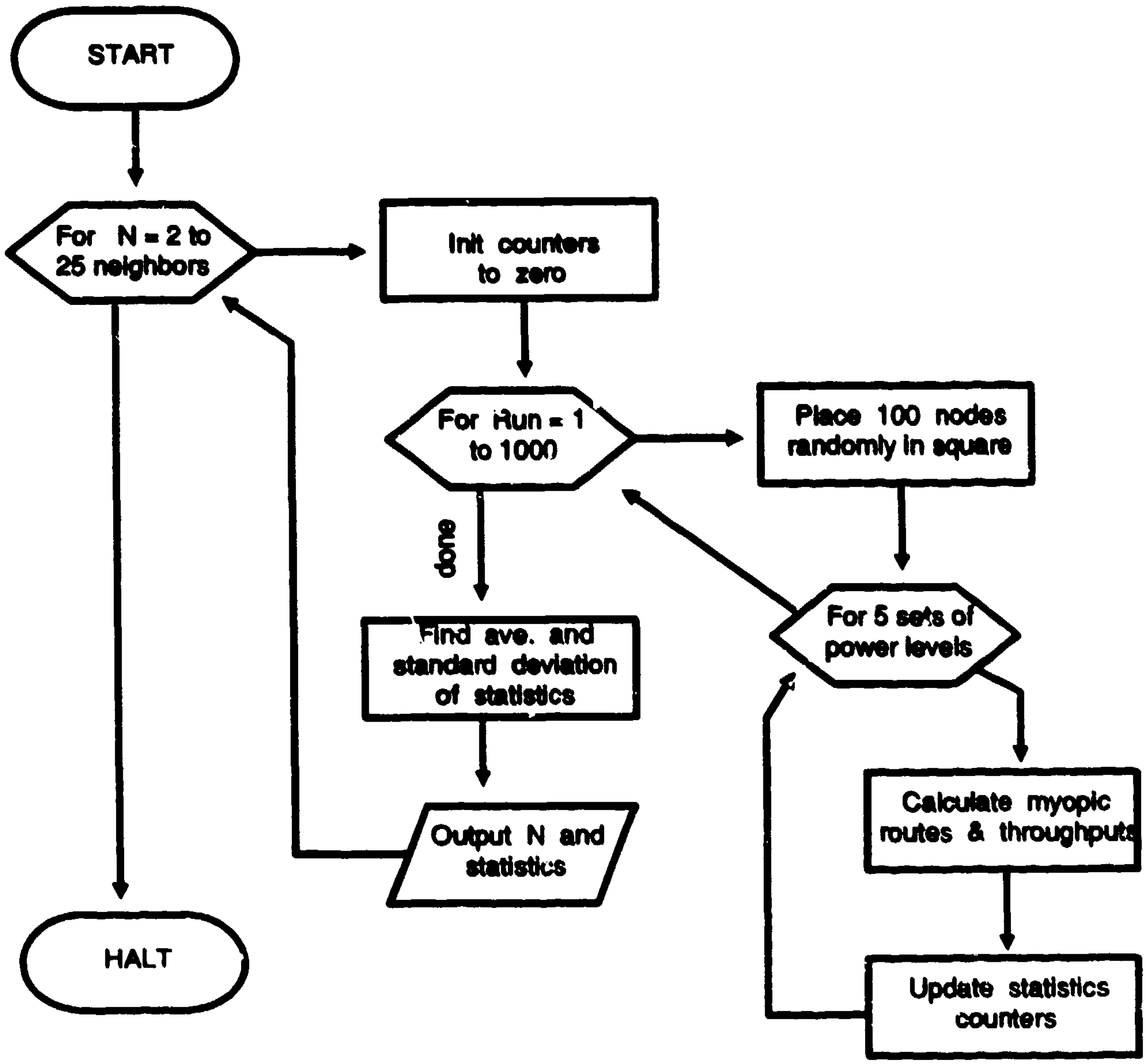


Figure 6-8. Discrete Power Level Myopic Simulation Flowchart

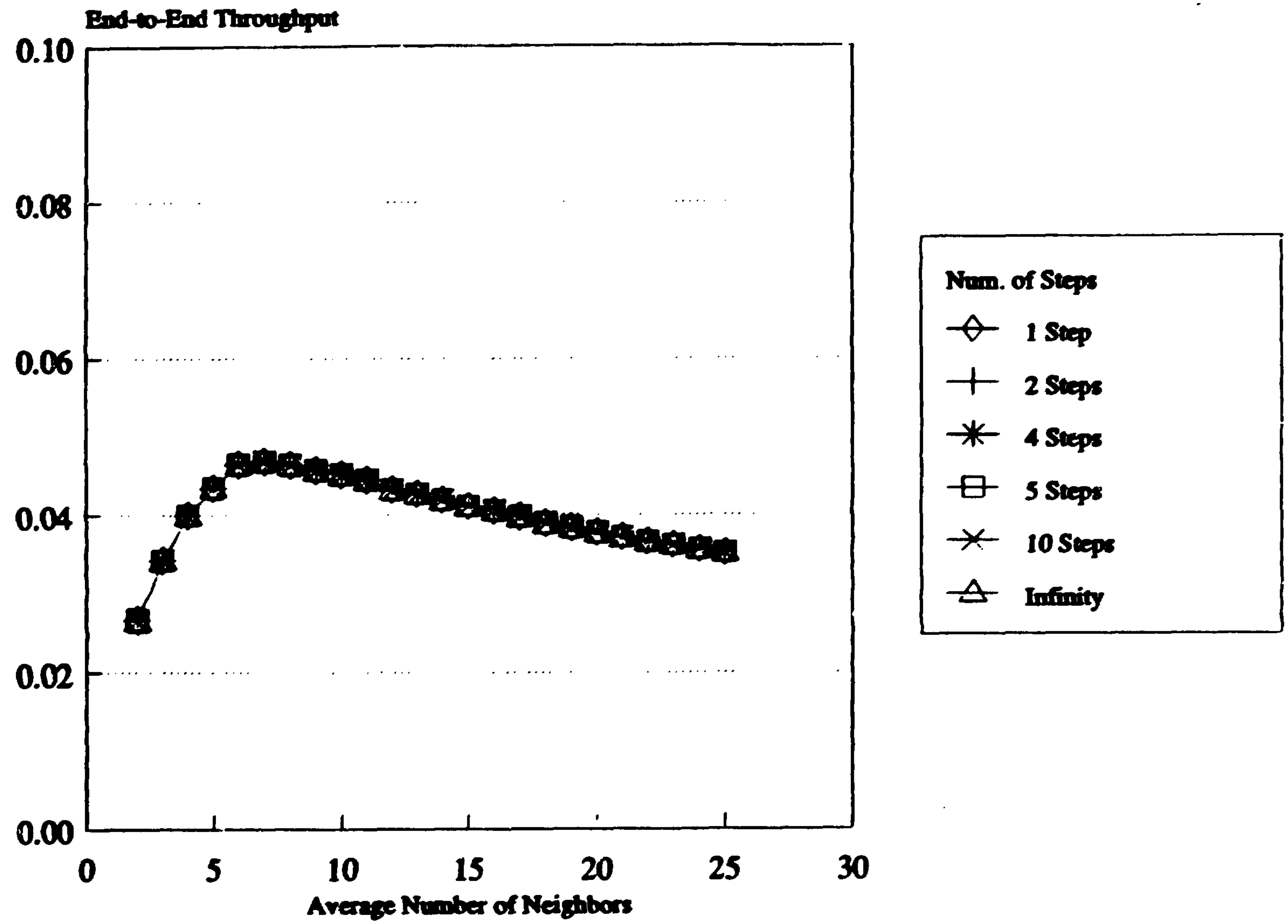


Figure 6-9. MFR End-to-End Throughput

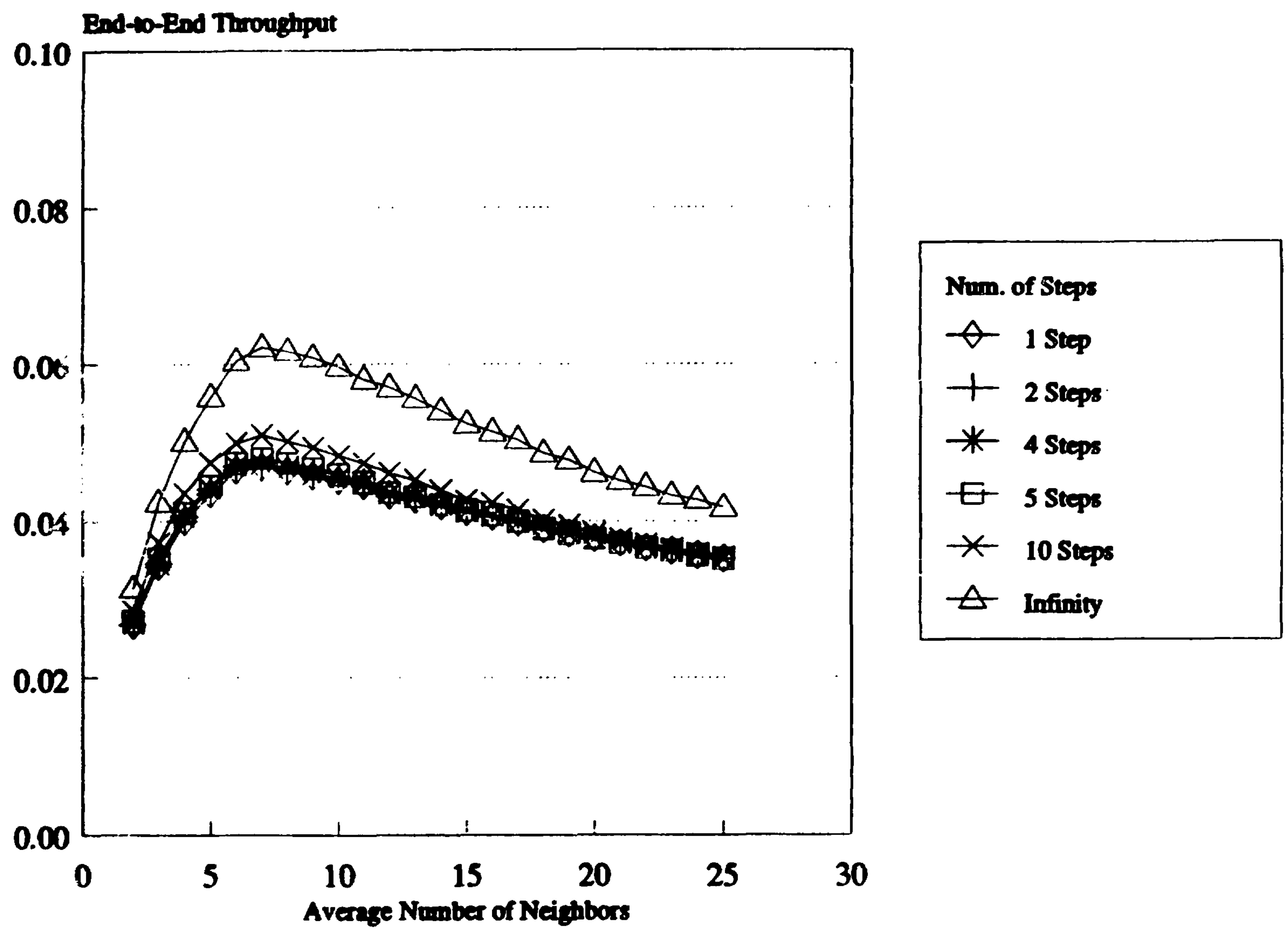


Figure 6-10. MVR End-to-End Throughput

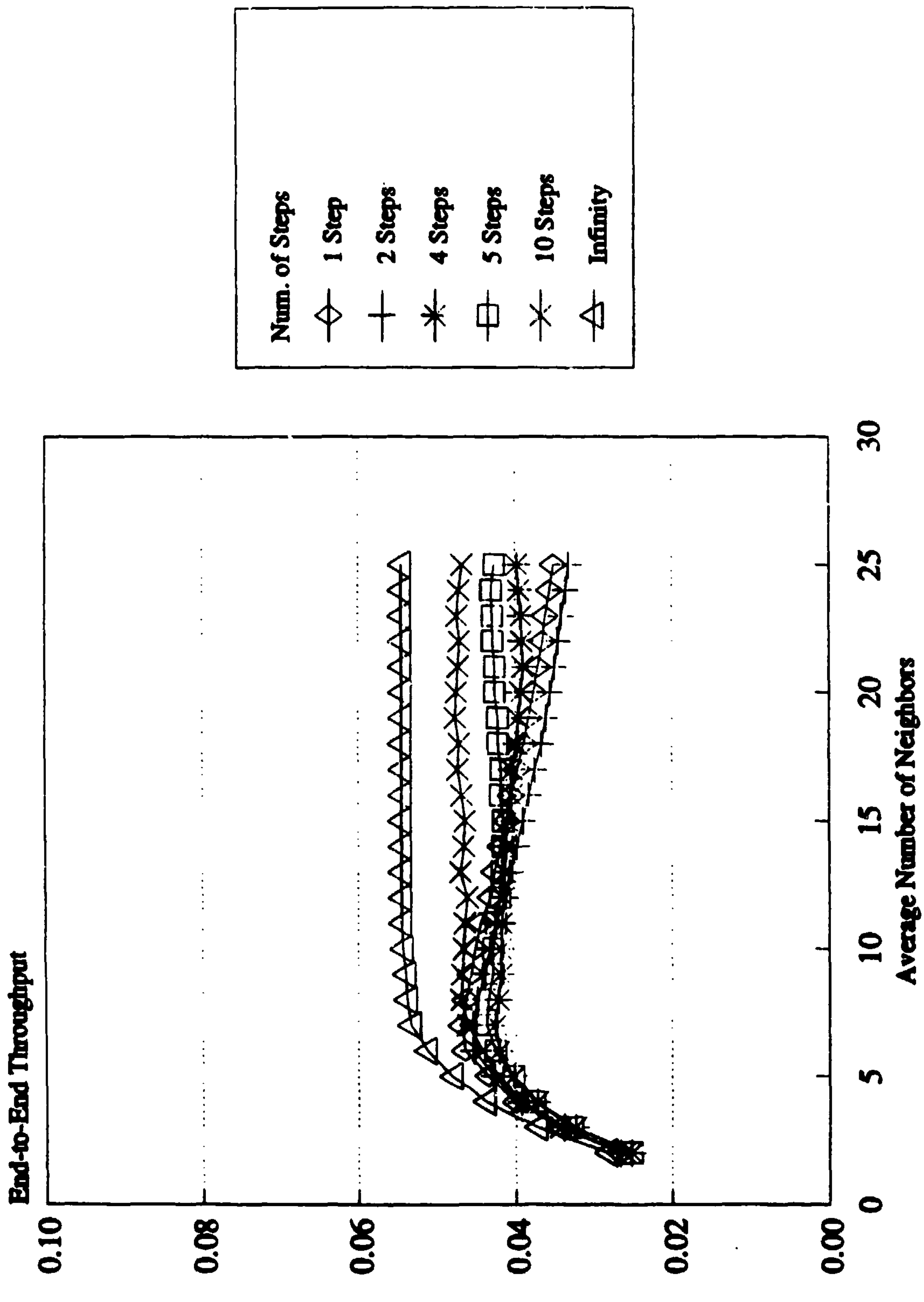


Figure 6-11. NFP End-to-End Throughput

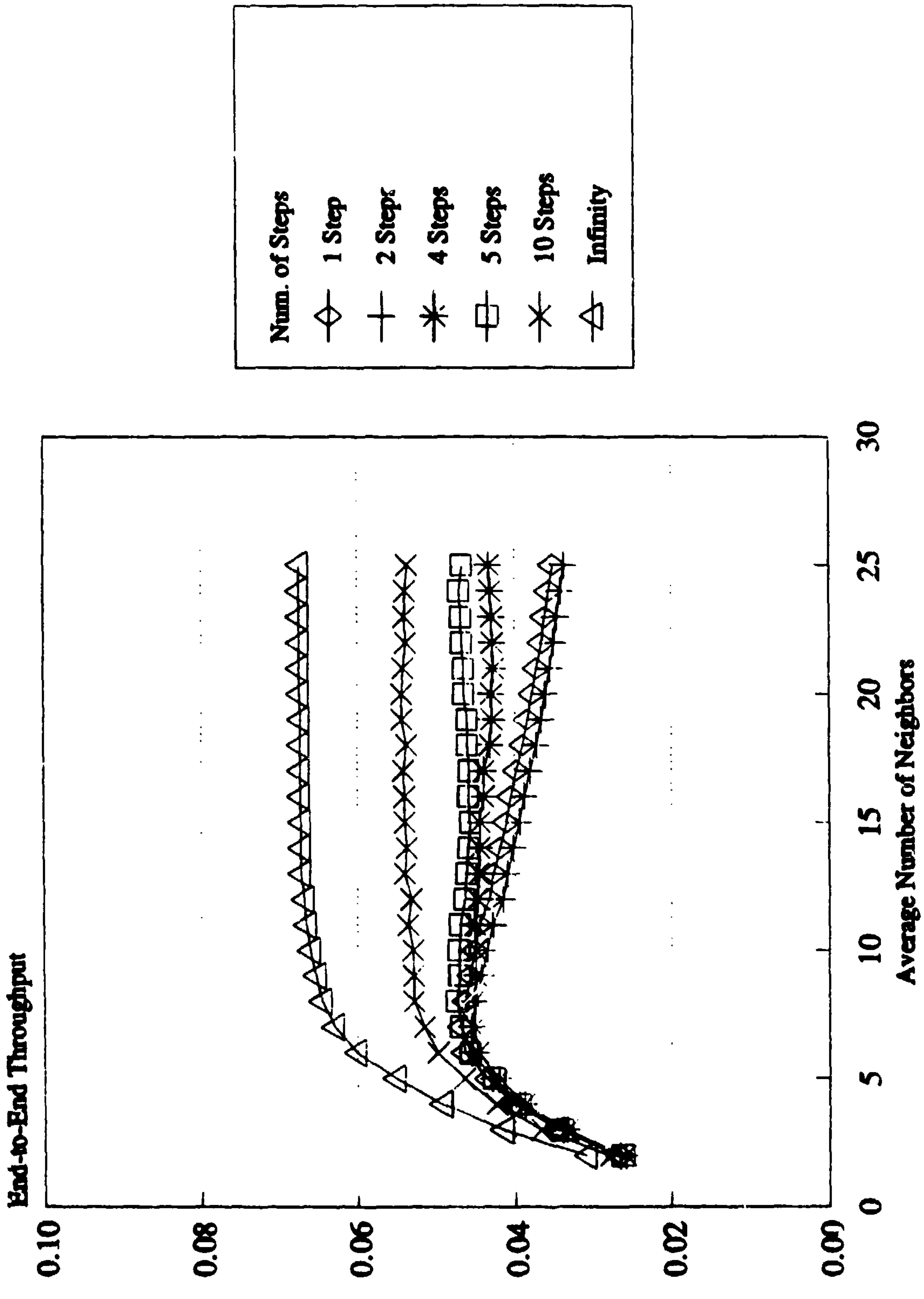


Figure 6-12. LAR End-to-End Throughput

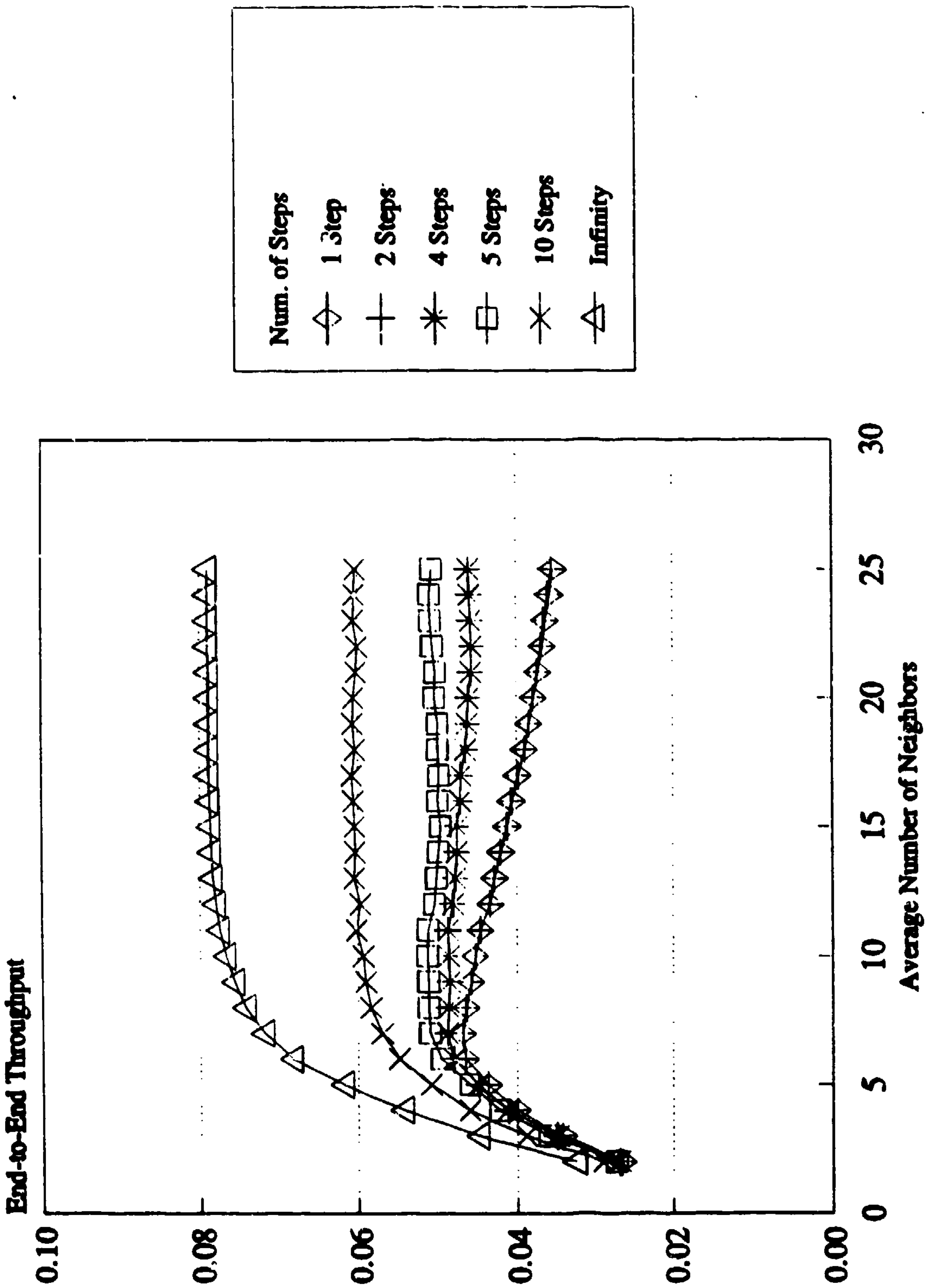


Figure 6-13. LIR End-to-End Throughput

show noticeable improvement with an infinite number of power steps, they do not show appreciable improvement with a small number of steps, such as ten, which will be found in real operational radios. LAR and LIR show a moderate amount of improvement with ten steps, but not with five steps or less.

Figure 6-14 shows the $Z\sqrt{\lambda}$ end-to-end throughput versus the number of power steps for the different myopic schemes for an average of five neighbors. Figures 6-15 through 6-18 show the similar graphs for an average of 7, 10, 15, and 25 neighbors, respectively. These graphs show that NFP and LAR actually perform worse with a few power steps, such as 2 or 5, than does MFR. LIR shows the best performance for all power steps in these graphs. For ten power steps, and only a few neighbors, we see that the LIR is best, followed by LAR, MVR, NFP, and MFR. For ten power steps and many neighbors, we see that LIR is best, followed by LAR, NFP, MVR, and MFR.

Figure 6-19 replots L/R" from Figure 6-5 against Rp(i)/R" for five power levels. Due to the random distribution of PRUs, a few PRUs will be within the smallest transmission ranges. Therefore, for only a few power steps, e.g., two or five, NFP and LAR will pick the same next-PRU as MFR and MVR except for the few times when a PRU is within the smallest transmission range. However, the efficiency of a PRU within the smallest range is likely to be smaller than the efficiency of the PRU chosen by MFR and MVR for small neighborhood degrees so that when NFP and LAR differ from MFR and MVR, they actually lower their overall performance as seen in Figures 6-14 through 6-18.

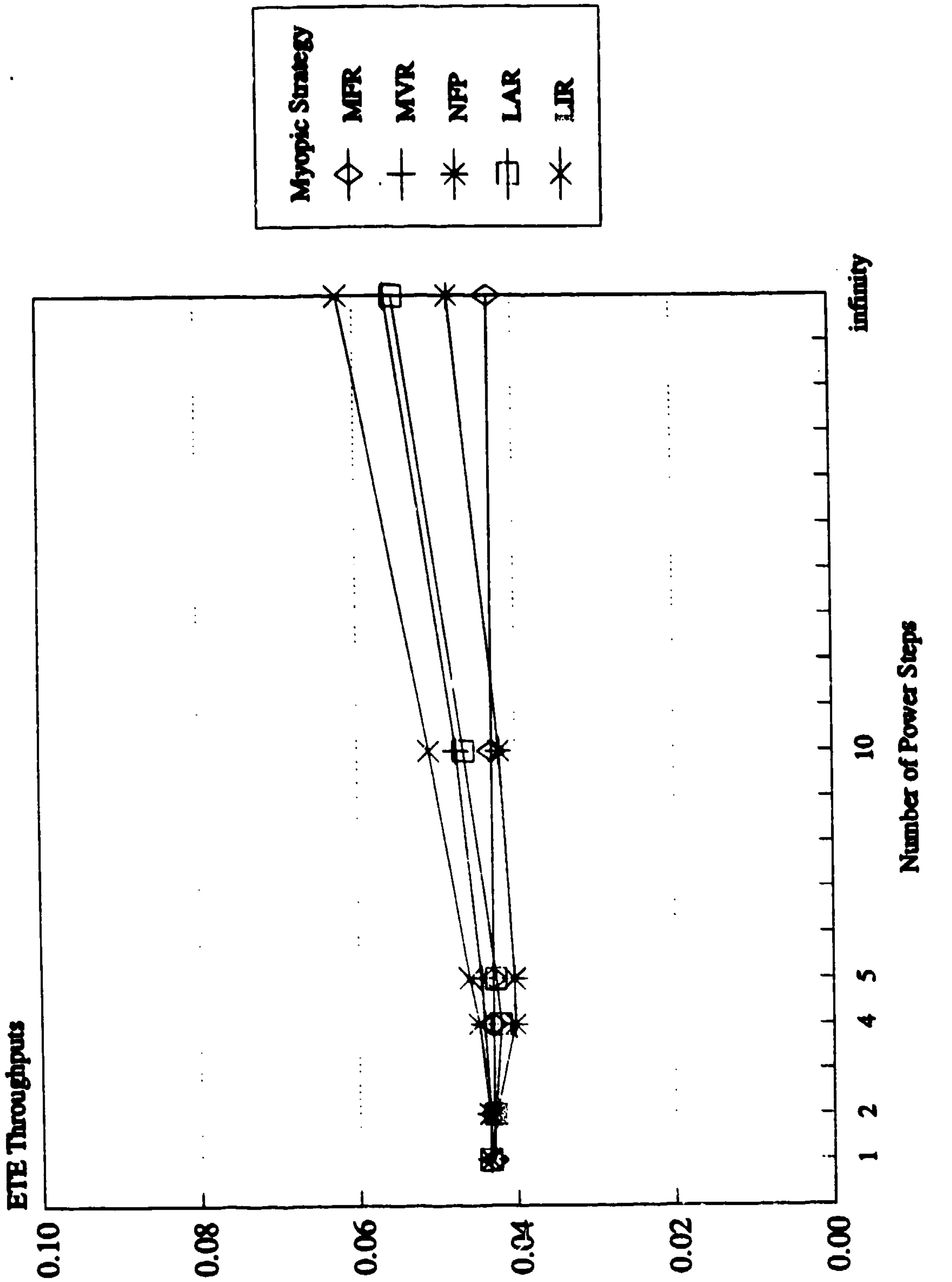


Figure 6-14. Throughput Comparisions for Average of 5 Neighbors

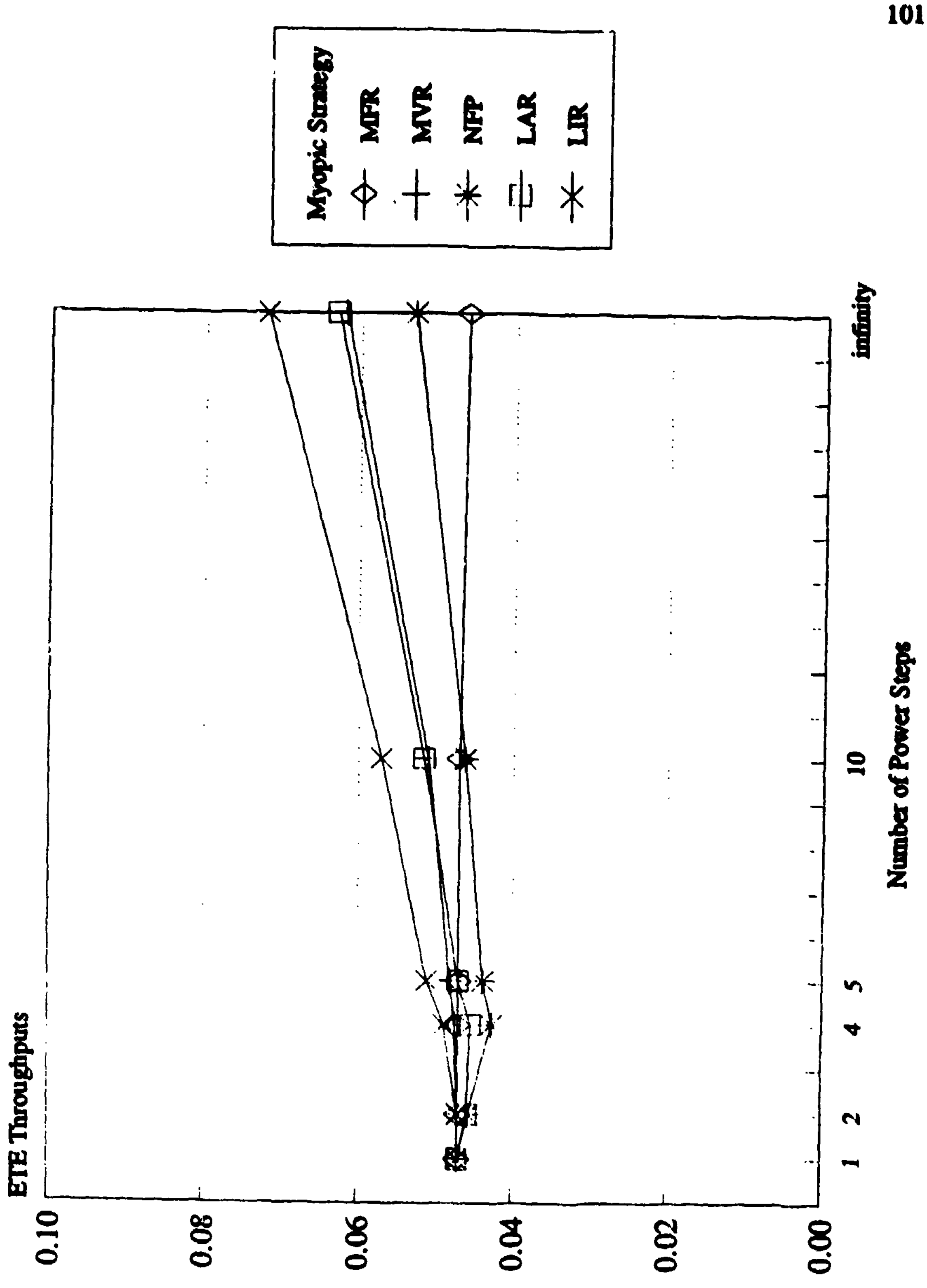


Figure 6-15. Throughput Comparisions for Average of 7 Neighbors

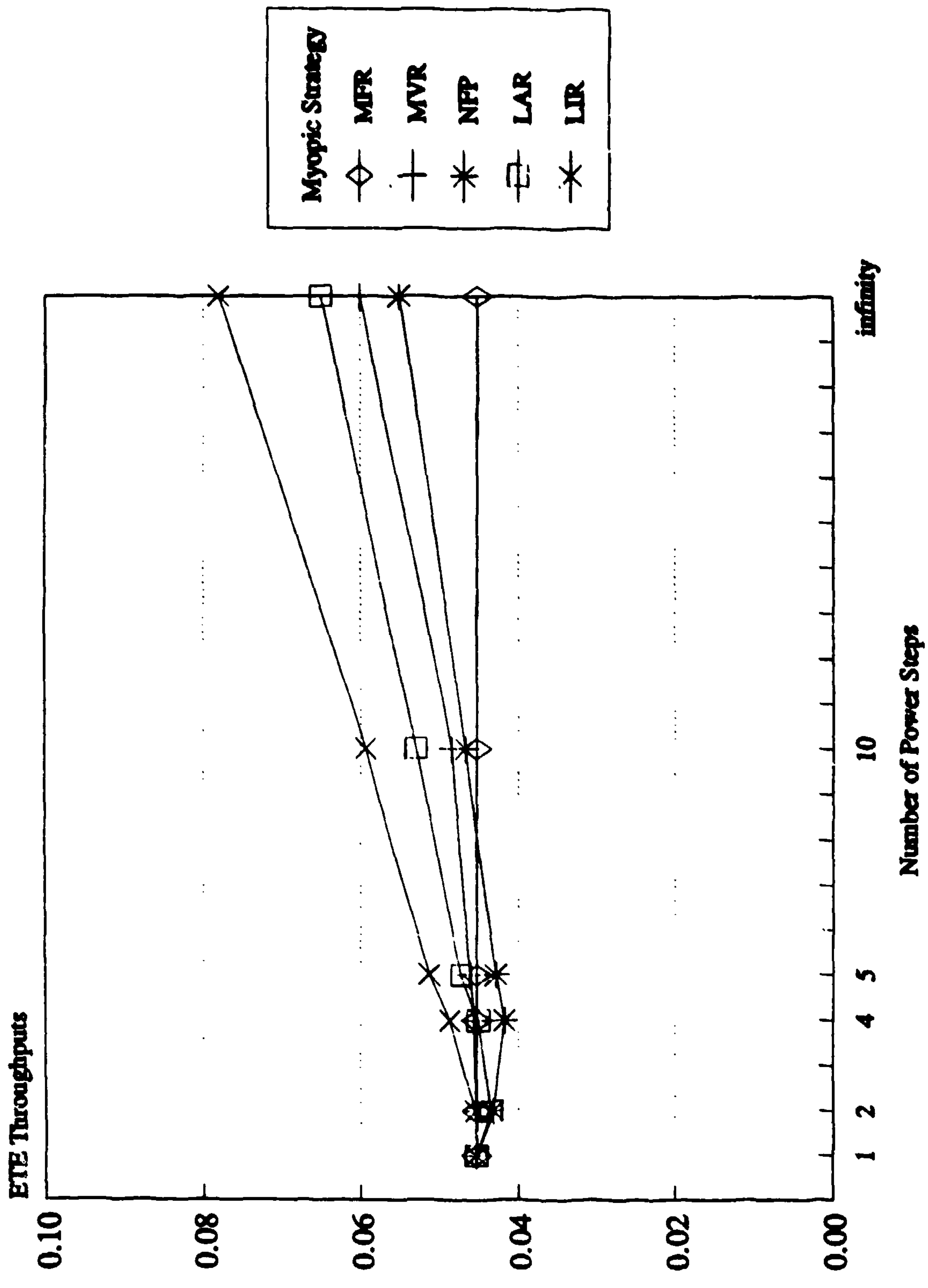


Figure 6-16. Throughput Comparisions for Average of 10 Neighbors

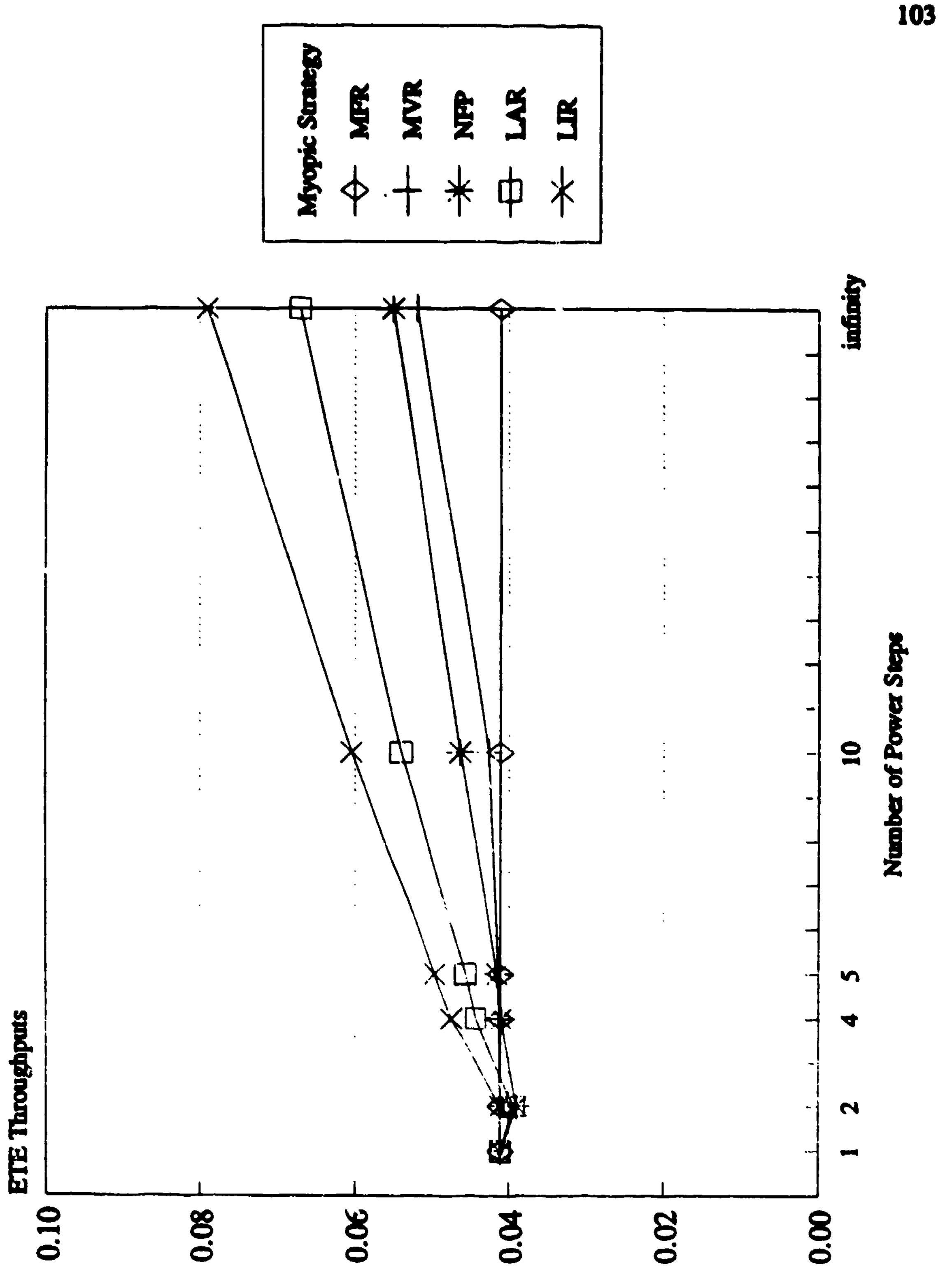


Figure 6-17. Throughput Comparisions for Average of 15 Neighbors

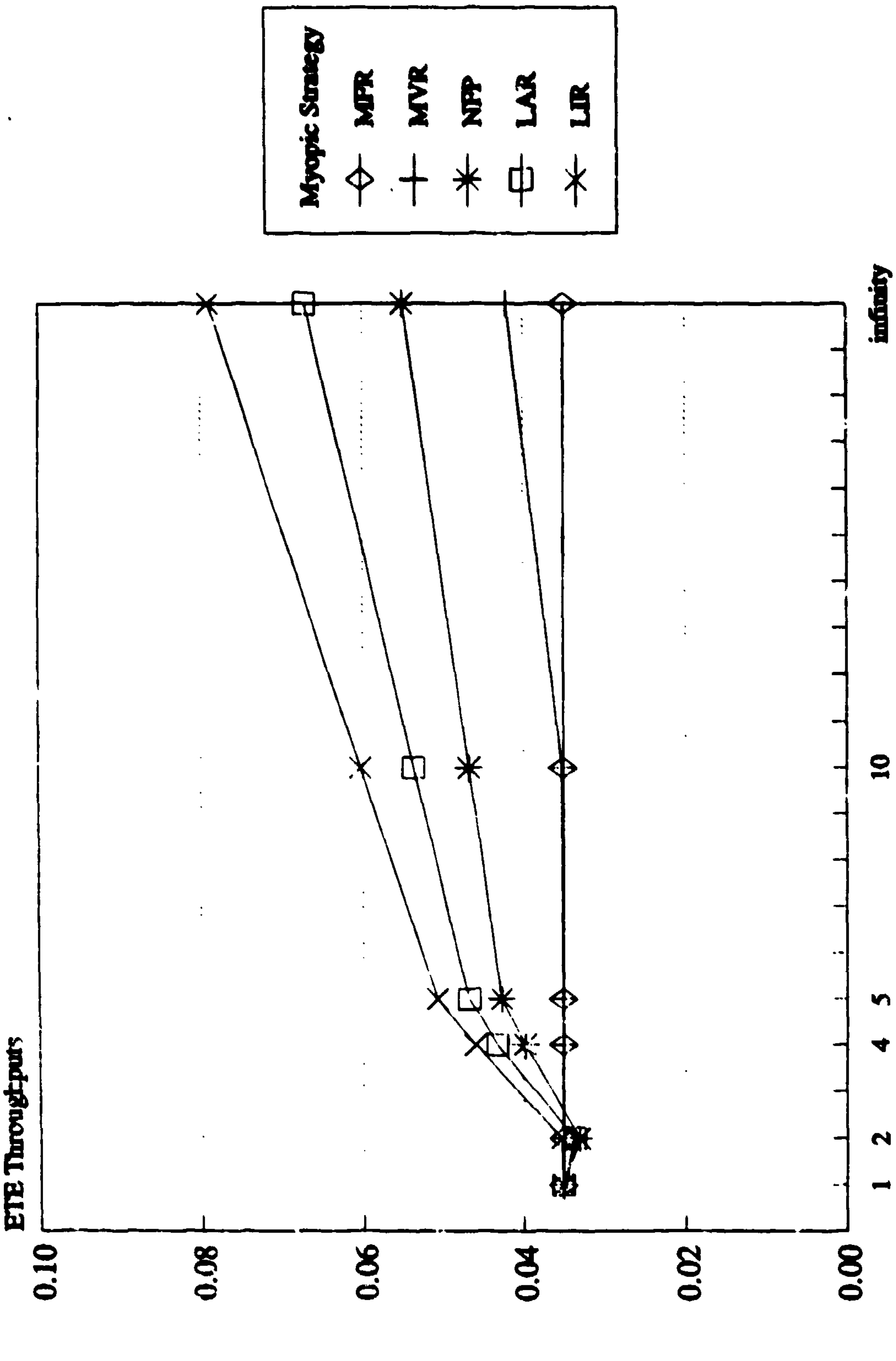


Figure 6-18. Throughput Comparisions for Average of 25 Neighbors

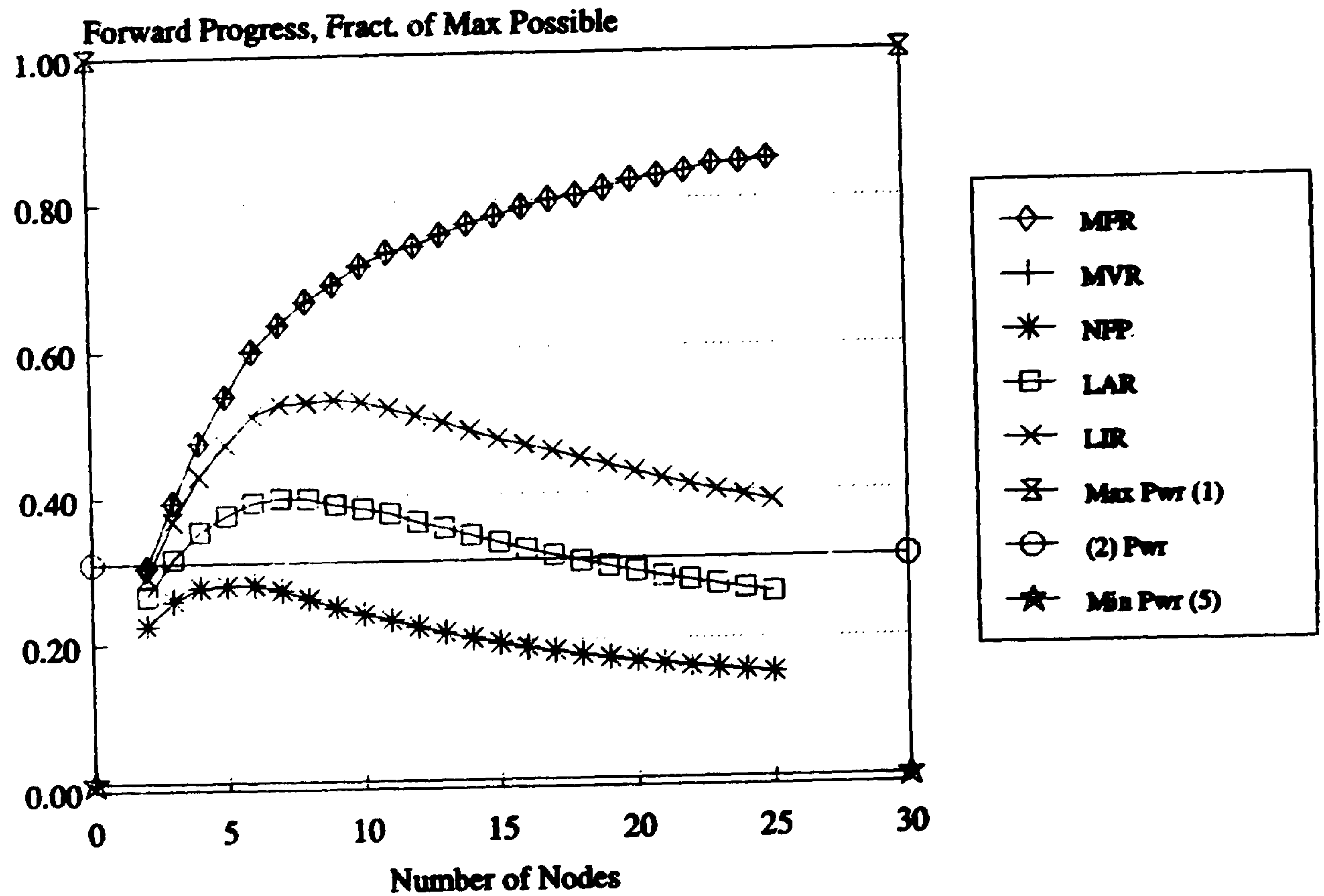


Figure 5-19. Forward Progress and Discrete Transmission Ranges

6.4 Conclusions

These graphs indicate that LIR has better PRNET performance than MFR or MVR, implying that operational PRNETs would improve their performance by using LIR and dynamic power control.

The simulation results indicate that the improvement of MVR and LIR over MFR appears to be small for a small number of discrete power steps. This result arises from the assumptions that all PRUs at a distance R will receive a transmission at the same power level. Section 2.2.1.2 discussed that this is a poor assumption, since PRUs at the same distance may have variances of up to 24 dB between their actual receive power levels. This variation of power levels in operational PRNETs means that a few power levels should provide a greater improvement over no dynamic power control than observed in the simulation results of Section 6.3.

7. MULTIHOP SIMULATION OF LIR

7.1 Introduction

Chapter 6 showed the results of simulations comparing myopic LIR with the previous myopic strategies. Because of the inherent short sided nature of myopic strategies, we also simulate LIR and minimum-hop routing with and without power control in a multi-hop network including actual packet forwarding with queueing delays and retransmissions of interfered packets.

Section 7.2 describes the simulation model and Section 7.3 discusses the simulation results.

7.2 The Multihop Simulation

The multihop PRNET simulator was built as several modules with four major parts: (1) a network generator, (2) a route generator, (3) a traffic simulator, and (4) a statistics reducer. A flow chart of the overall flow of the simulator is shown in Figure 7-1.

Input parameters to the simulation include the number of PRUs in the PRNET; the maximum possible transmission range; the uniform offered traffic rate in packets per PRU per time slot; the length of the simulation in time slots, the Aloha transmission interval, i.e., the number of time slots over which to randomize a transmission; the maximum number of times a PRU is to (re)transmit a packet before discarding it; the PRU packet queue length, i.e., how many packets a PRU can store before it has to discard a received packet; and how many runs to make

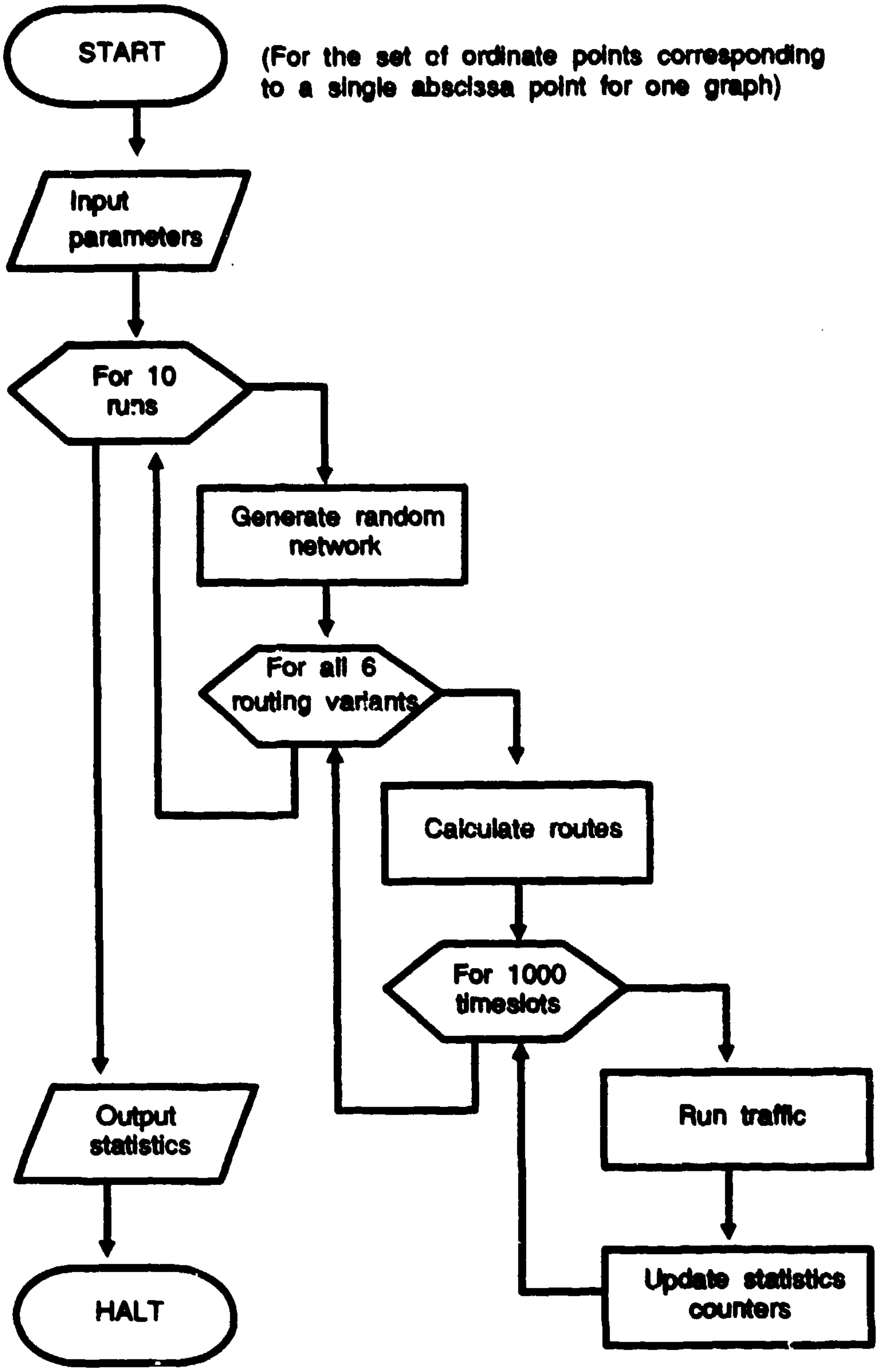


Figure 7-1. The Multihop Simulation Flowchart

using an identical set of simulation parameters but with different initial random seeds.

The network generation phase creates a random network with the specified input number of PRUs which are randomly placed at integer vertices of a 50-by-50 unit square as a Poisson process. Note that we allow multiple PRUs to occupy the same vertex, i.e., it is possible for two PRUs to be a distance of zero from each other. The average density, λ, is:

$$\lambda = \text{(number of PRUs)} / \text{(area of square)} = \text{(number of PRUs)} / (2500 \text{ units}^2)$$

Thus the number of PRUs within a circle of radius R which is completely contained within the 50 by 50 square is:

$$\lambda \pi R^2 = \pi \text{ (number of PRUs) } R^2 / 2500$$

The simulation tested the three variants of minimum-hop routing and LIR discussed in Chapter 5, i.e., MinHop-nap, MinHop-ap, Min-Hop-np, LIR-nap, LIR-ap, and LIR-np.

For both routing strategies with power control, the simulation also examined the use of acknowledgments with enough power to reach both the previous and next PRUs and not using acknowledgments, i.e., with only enough power to reach the next PRU. Note that the MinHop-ap routing table is identical to the MinHop-nap routing table, while their processing in the traffic simulation is different. The LIR-ap and LIR-nap routing tables are different as well as the processing in the LIR traffic simulation. When the simulated PRNET is fully connected, the MinHop-np and LIR-np routing tables are identical.

The multihop traffic simulation model uses the same channel model as the basic myopic simulation did in Section 6.2, namely that the PRNET is using narrow-band signaling with zero capture, that slotted Aloha is the channel access protocol, and that the rf signal propagates according to the threshold hearing function. The narrow-band signaling with zero capture means that if two PRUs overlap in time at the same PRU, they will destructively interfere with each other so that neither packet can be received correctly.

A uniform offered traffic model was used, which means that each PRU generates packets to every other PRU with the same probability. This probability was input as the uniform offered traffic rate per PRU per time slot. Basically, every PRU generated a random number every time slot. If the random number were less than the offered traffic rate, then the PRU generated a packet for forwarding through the PRNET. If a packet were generated, then the PRU generated a random number to determine which PRU would be the destination of the packet.

Note that when the transmission range is small, we sometimes had partitioned networks. When building the routing tables for the partitioned network, we set the next PRU in the route to zero to indicate that a route did not exist. Then the traffic simulator would discard packets at the source PRU if the routing table indicated that a route did not exist.

The packet buffer queue at each PRU was designed as a first-in, first-out (FIFO) queue, with newly generated or received packets placed at the end. If the queue is full, determined by the simulation packet queue length parameter, then the packet is discarded. When a PRU is allowed to transmit, it picks the first packet in the queue.

If multiple transmitted packets overlap at a PRU-i, including a transmission by PRU-i, then interference is said to occur and the packet cannot be received correctly by PRU-i. If the packet were received correctly at the next PRU in the route, the packet is discarded by the transmitting PRU. The simulation assumes instantaneous "free" acknowledgments of successfully received packets. Therefore, if a transmitted packet is received correctly by the next PRU, the transmitting PRU discards the packet from its queue. If a transmitted packet is not received correctly, the packet stays at the front of the queue for retransmitting unless the packet has been transmitted the maximum possible number of times, at which time the packet is discarded.

The simulation used a uniform probability function to determine the Aloha transmission probability. Therefore, if the uniform interval is X slots, the probability of transmission by a PRU in any given slot is 1/X. Because the network performance turned out to be very dependent upon the transmission probability, the simulation supported three methods of calculation. First, a constant interval (in slots) could be input that all PRUs would use; or second, a coefficient could be input that would be multiplied by the average network degree of the actual simulated network; or third, a coefficient could be input that would be multiplied by the actual network degree of the transmitting PRU, i.e., the hitting degree discussed by Silvester [Silve80].

For MinHop-np and LIR-np, the simulator transmitted each packet using the simulation maximum transmission range parameter. For MinHop-ap and LIR-ap, the simulator transmitted each packet using the minimum range needed to reach both the previous and next PRUs, as discussed in Section 3.4. Note that, because the simulation assumed instantaneous free acknowledgments, the destination PRU did not transmit back an active acknowledgment. For MinHop-nap and LIR-nap, the simulator transmitted each packet using the minimum range needed to reach the next PRU.

The total end-to-end throughput was defined to be the number of packets that reached their destination during the run of the traffic simulation. Therefore, the average end-to-end throughput per slot is the total end-to-end throughput divided by the number of time slots over which the simulation was run. The end-to-end delay is the average number of time slots it took to deliver packets from their source to their destination.

We discovered that we could obtain the same maximum network throughput using the three methods of calculating the transmission probability. However, using a constant simulation transmission probability parameter requires many simulation runs since the average neighborhood size is different depending upon the routing protocol being simulated. The results using a simulation coefficient parameter that is multiplied by the actual network degree of the transmitting PRU had more variance than did the results using a simulation coefficient parameter that is multiplied by the average network degree. Thus, using the first coefficient parameter would require more runs than using the second coefficient parameter to achieve an average result with the same degree of assurance. Therefore, we used the second coefficient parameter in all of the runs presented in this dissertation.

Experimentation with 25 node PRNETs suggested that 1000 slots were long enough for the traffic simulation to reach steady state for any single simulation run and that averaging over 10 simulation runs is sufficient to provide results with low variances. We always set the number of retransmissions and the transmit queue lengths to 999 so that no packets would be thrown away due to too many retransmissions or filled queues during the 1000 time slot traffic simulations.

7.3 Simulation Results

Several simulations were run to determine the optimal coefficient to use to obtain the transmission probability. Figure 7-2 shows the end-to-end throughput versus Aloha transmission coefficient for partially connected 10 node PRNETs. Figures 7-3 through 7-7 show similar graphs for fully connected 10 node PRNETs, partially and fully connected 25 node PRNETs, and partially and fully connected 50 node PRNETs. Although a value of 1.25 for the coefficient does not yield the maximum throughput for all cases, it yields a throughput close to the maximum for all cases. Therefore, we will use a value of 1.25 for the Aloha transmission coefficient for all of the rest of our simulations.

Figure 7-8 shows the end-to-end throughput per offered traffic rate, and Figure 7-9 shows the end-to-end delay per offered traffic rate for partially connected 10 node PRNETs. Figures 7-10 through 7-15 show similar graphs for fully connected 10 node PRNETs and partially and fully connected 25 node PRNETs. These graphs show that LIR with power control can support more traffic than Min-Hop with power control without adding an undue amount of additional end-to-end delay.

The end-to-end throughput and delay corresponding to an offered traffic of zero packets per PRU per slot were not obtained by running the traffic part of the simulation (as was done for all of the other simulation results), but were obtained by analysis. It is obvious that the end-to-end throughput, in the limit as the offered traffic approaches zero, is zero. Similarly, the end-to-end delay, in the limit as the offered traffic approaches zero, is the average number of

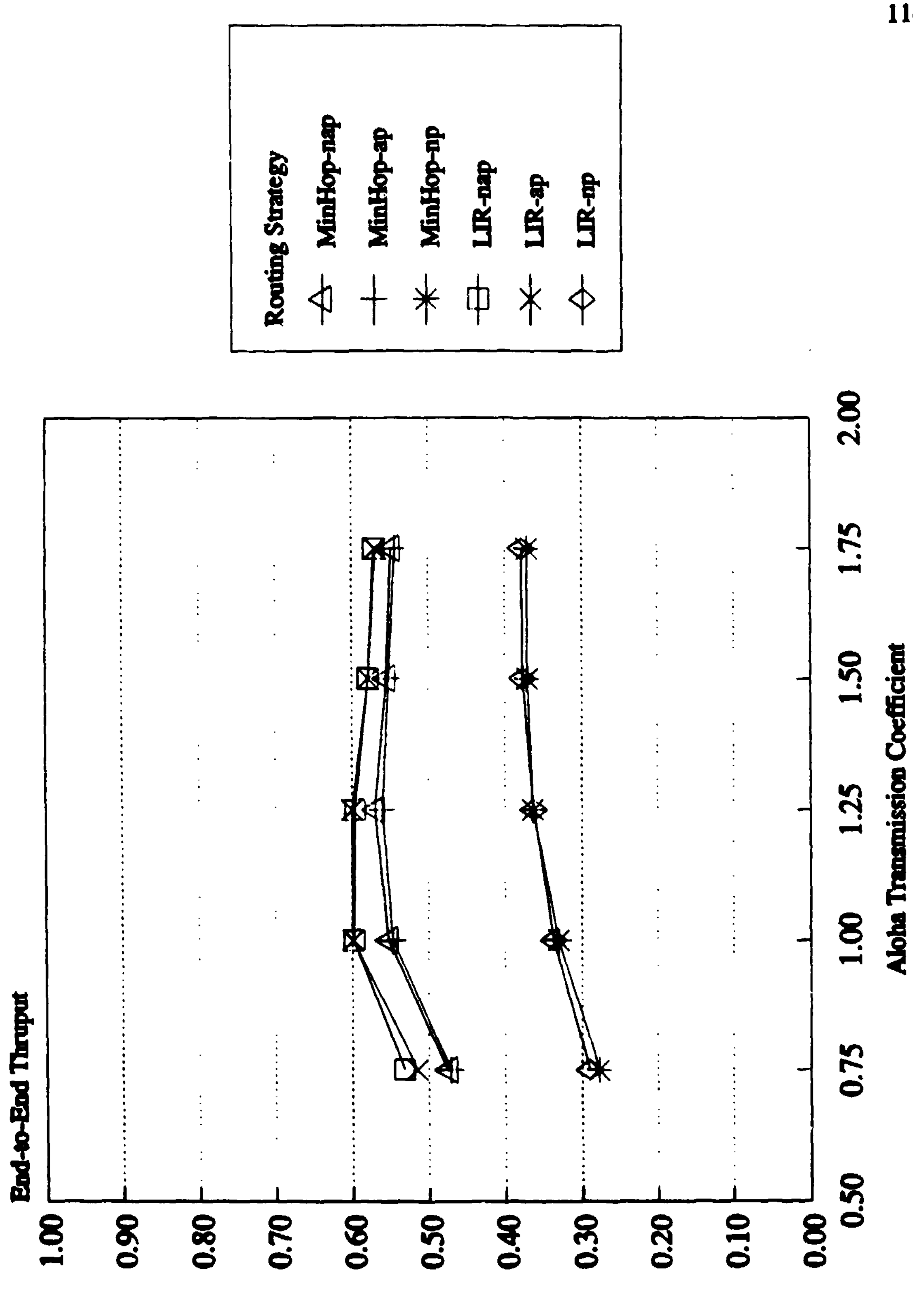


Figure 7-2. Throughput Versus Transmit Probability for 10 Node PRNETs with Transmit Radius = 40

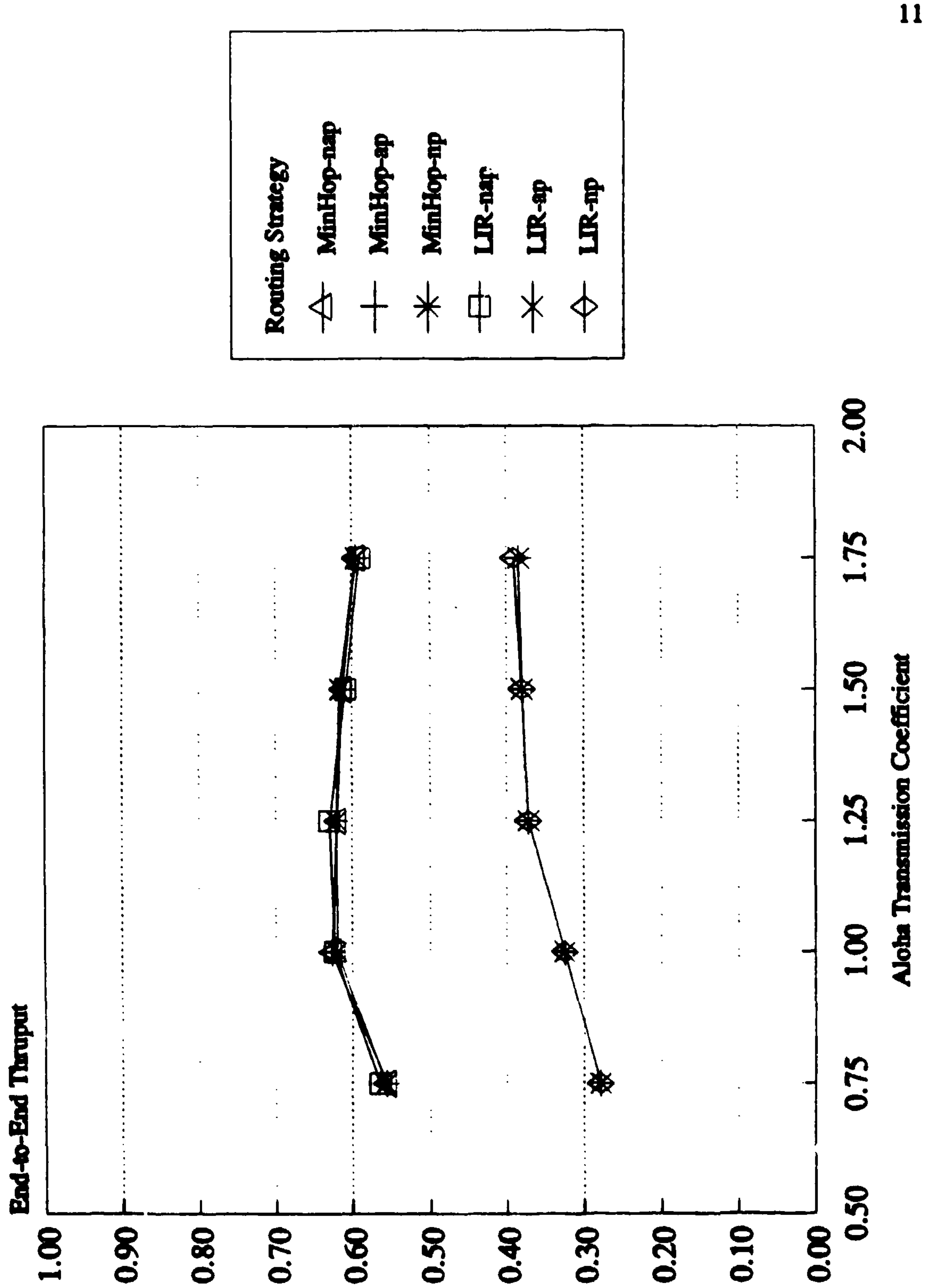


Figure 7-3. Throughput Versus Tranmsit Probability

for 10 Node Fully Connected PRNETs

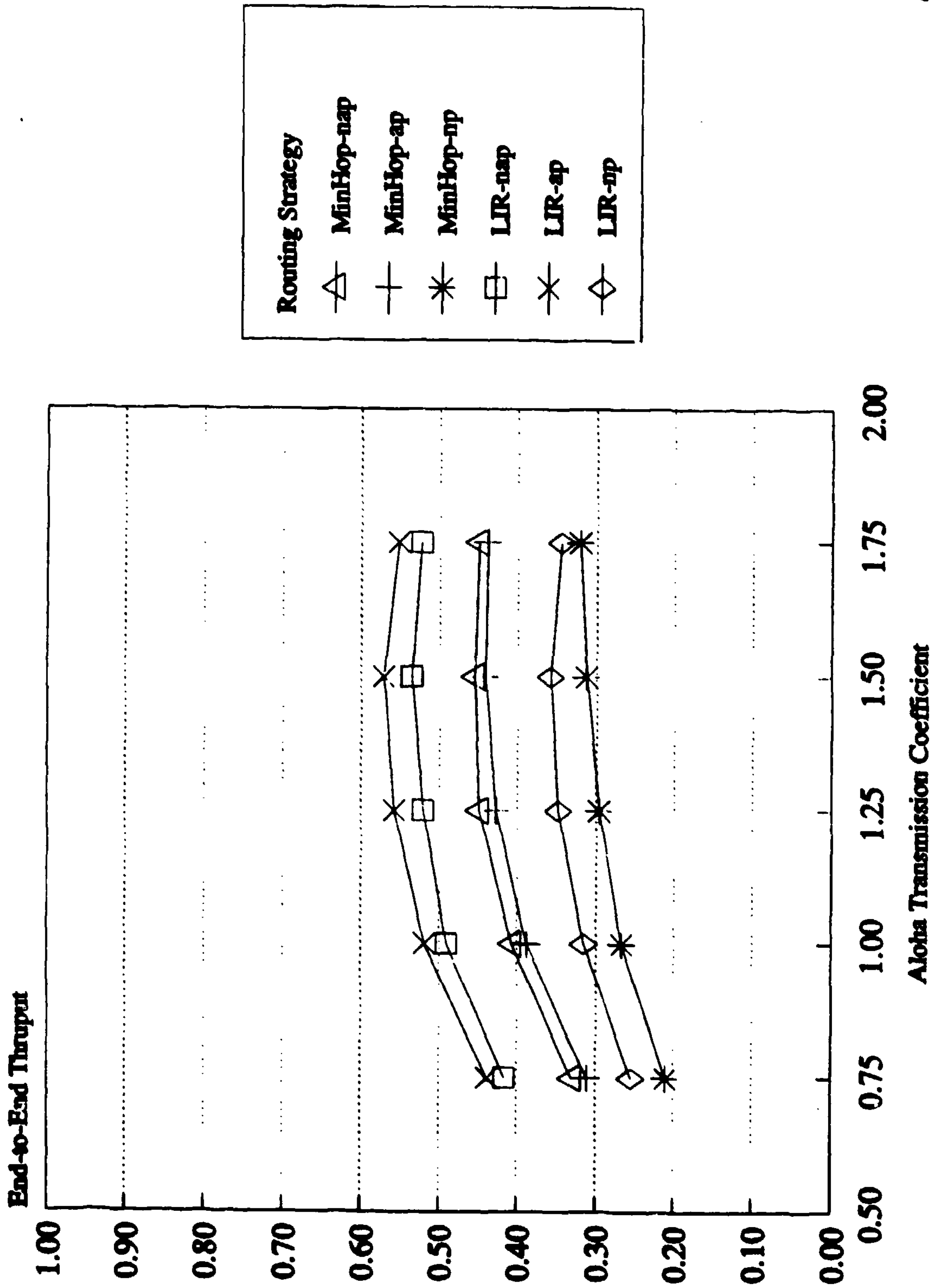


Figure 7-4. Throughput Versus Transmit Probability

for 25 Node PRNETs with Transmit Radius = 25

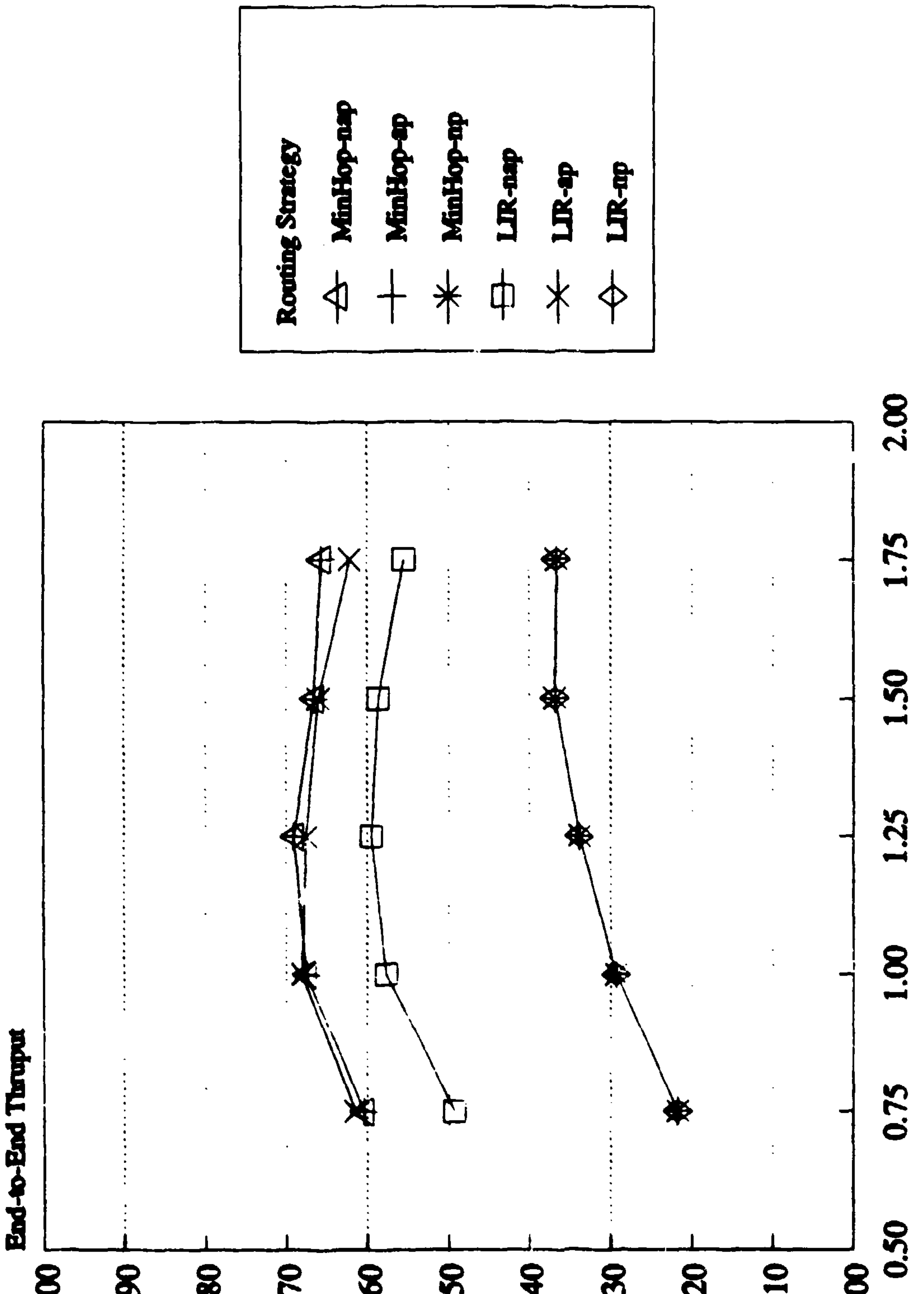


Figure 7-5. Throughput Versus Transmit Probability

for 25 Node Fully Connected PRNETs

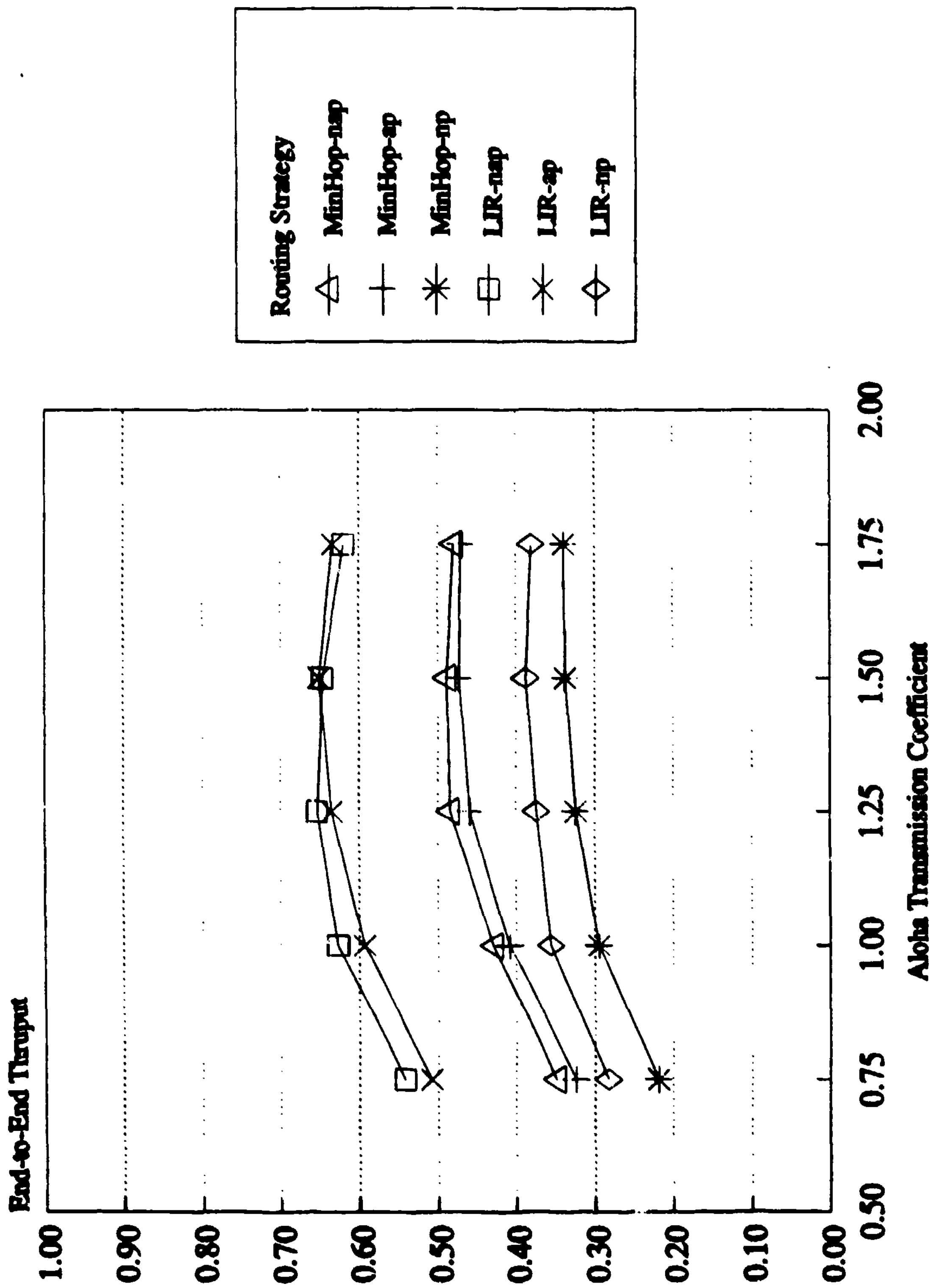


Figure 7-6. Throughput Versus Transmit Probability

for 50 Node PRNETs with Transmit Radius = 18

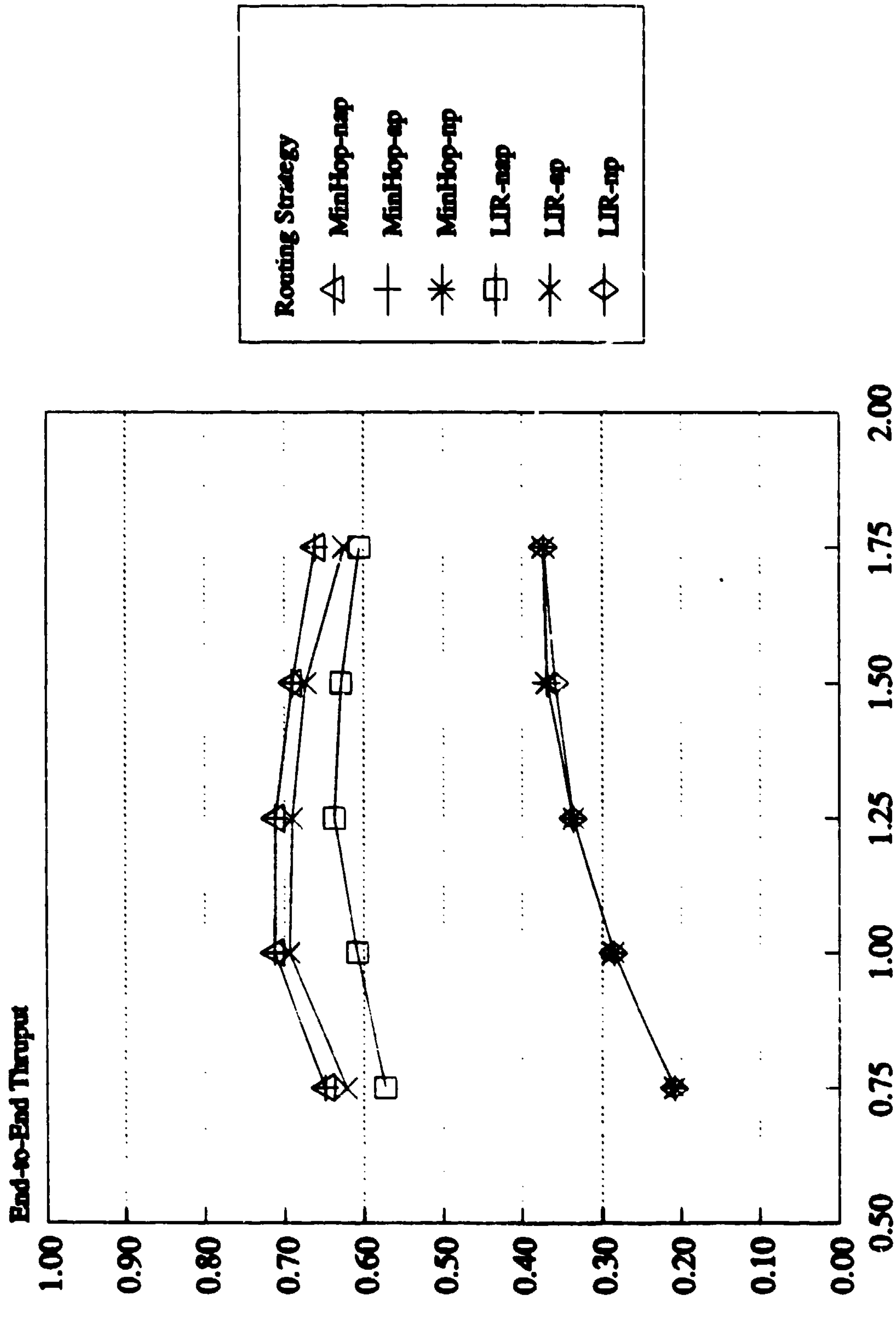


Figure 7-7. Throughput Versus Transmit Probability

for 50 Node Fully Connected PRNETs

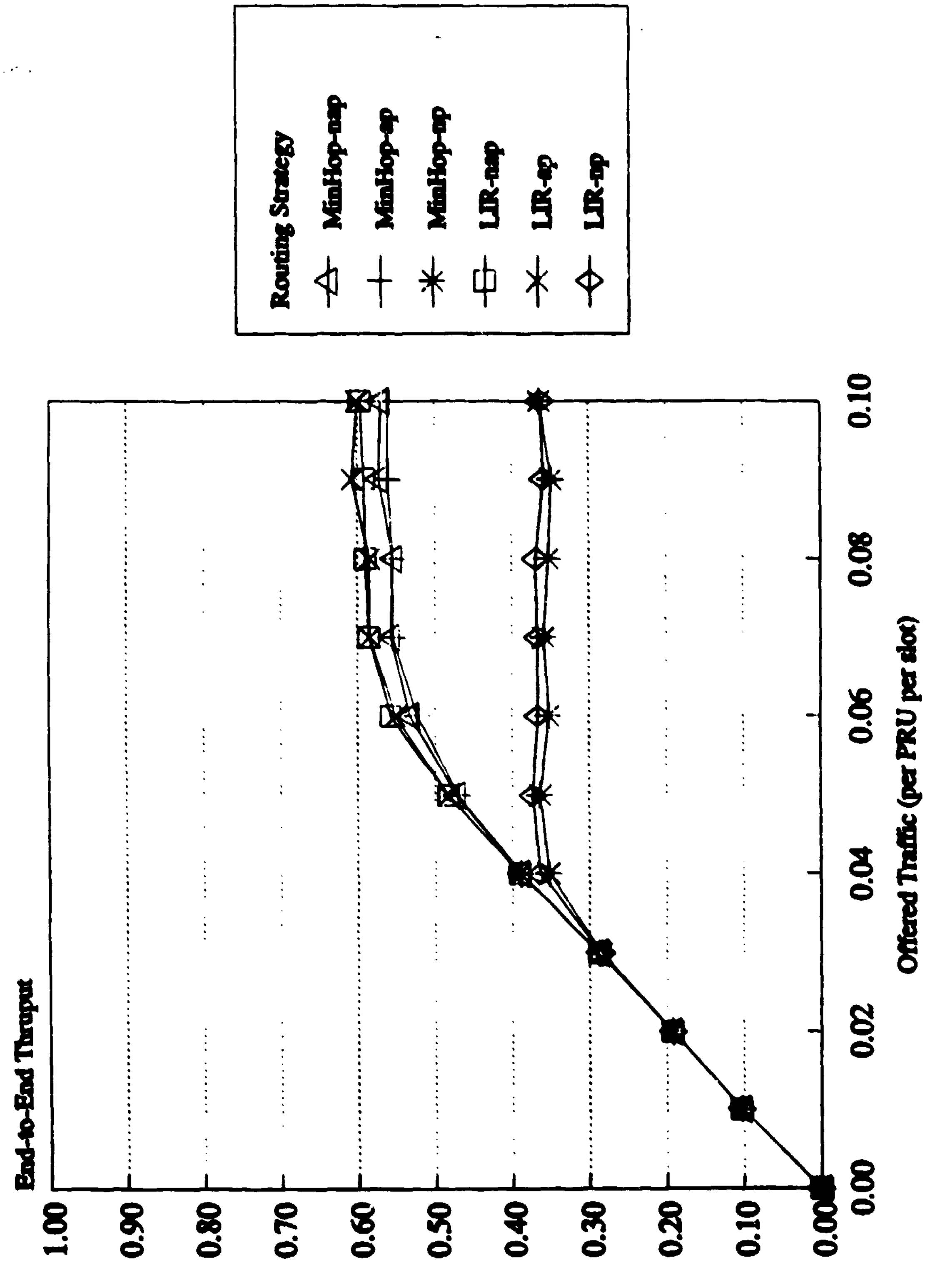


Figure 7-8. Throughput Versus Offered Traffic

for 10 Node PRNETs with Transmit Radius = 40

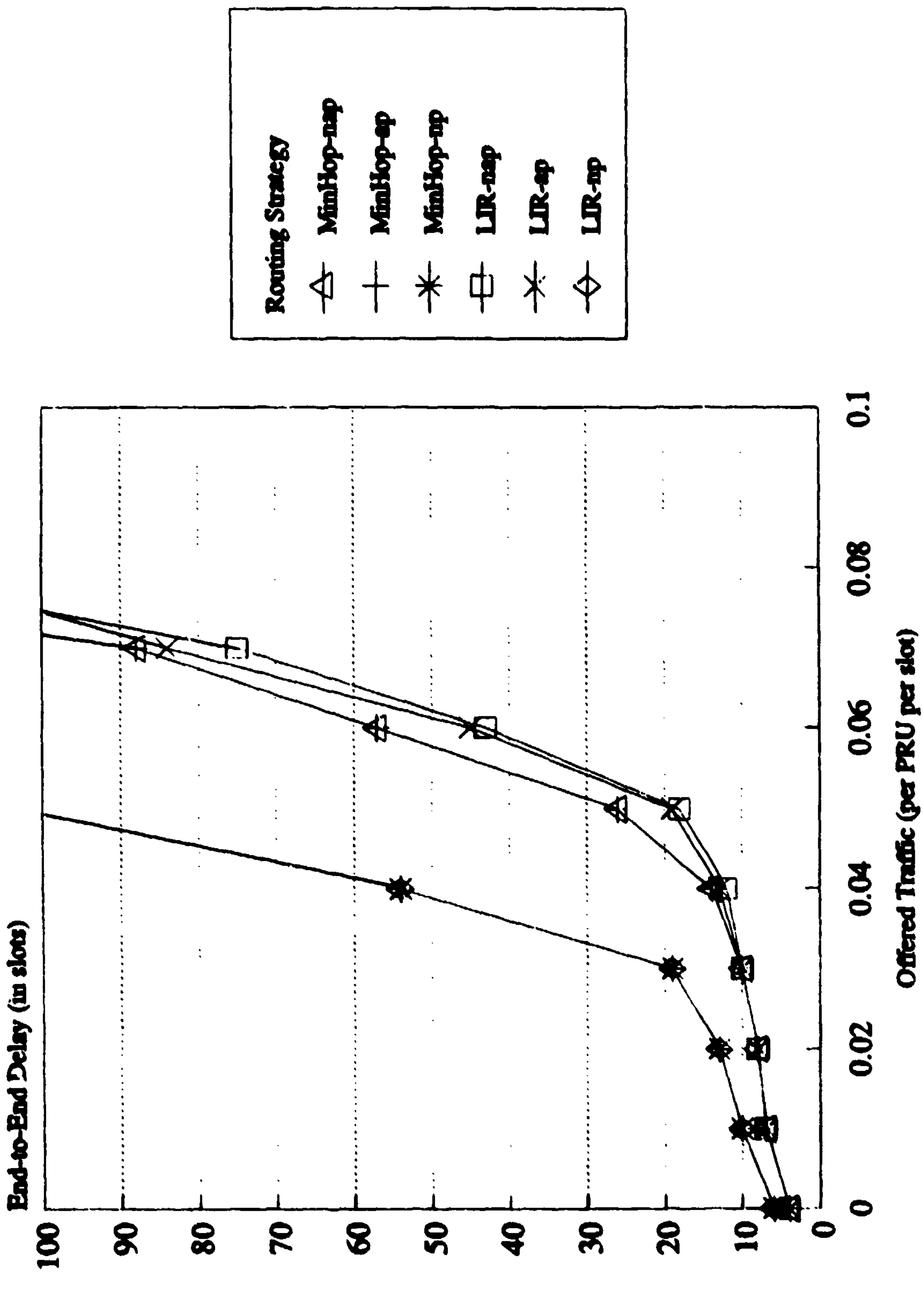


Figure 7-9. End-to-End Delay Versus Offered Traffic for 10 Node PRNETs with Transmit Radius = 40

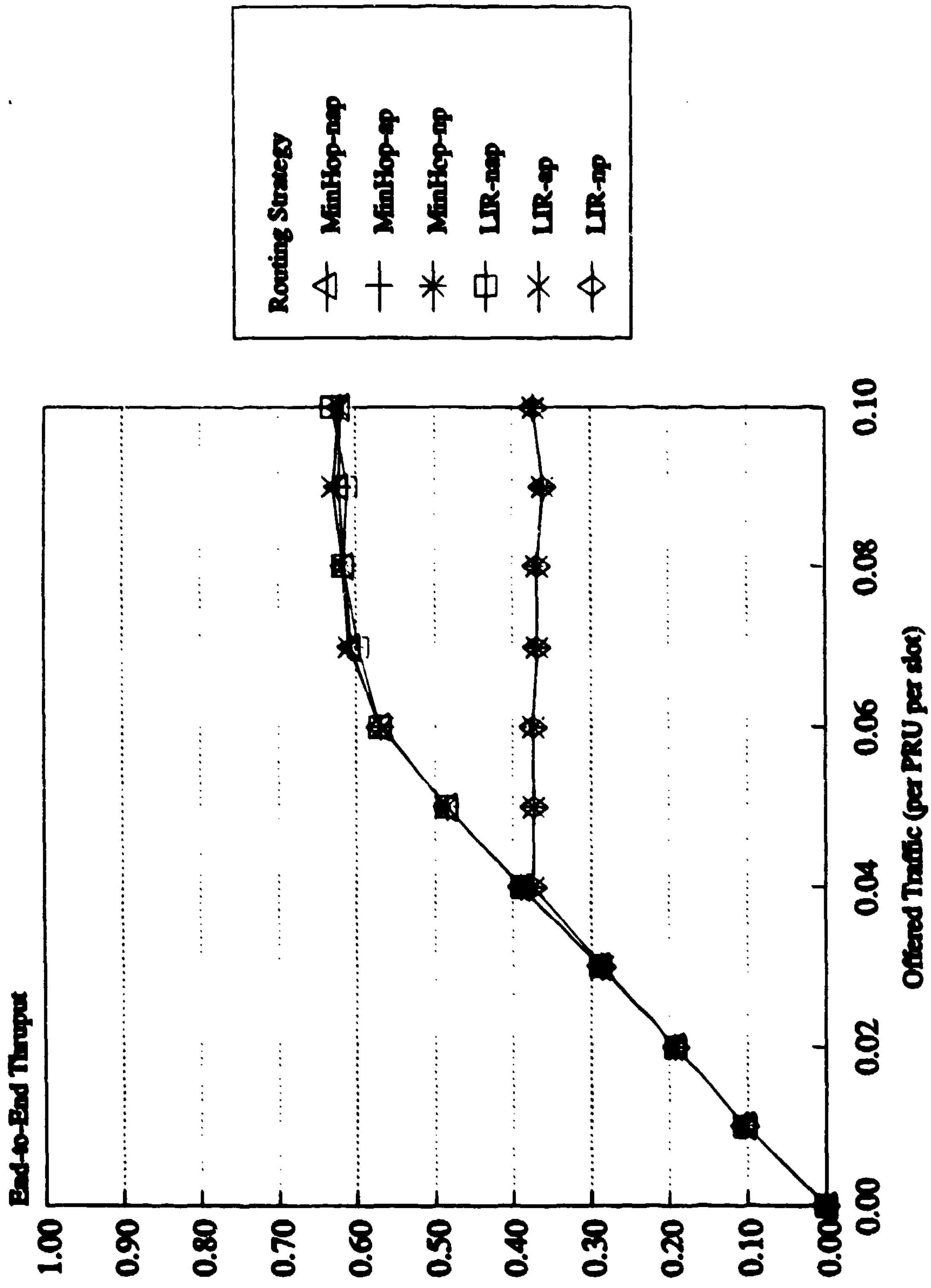


Figure 7-10. Throughput Versus Offered Traffic for 10 Node Fully Connected PRNETs

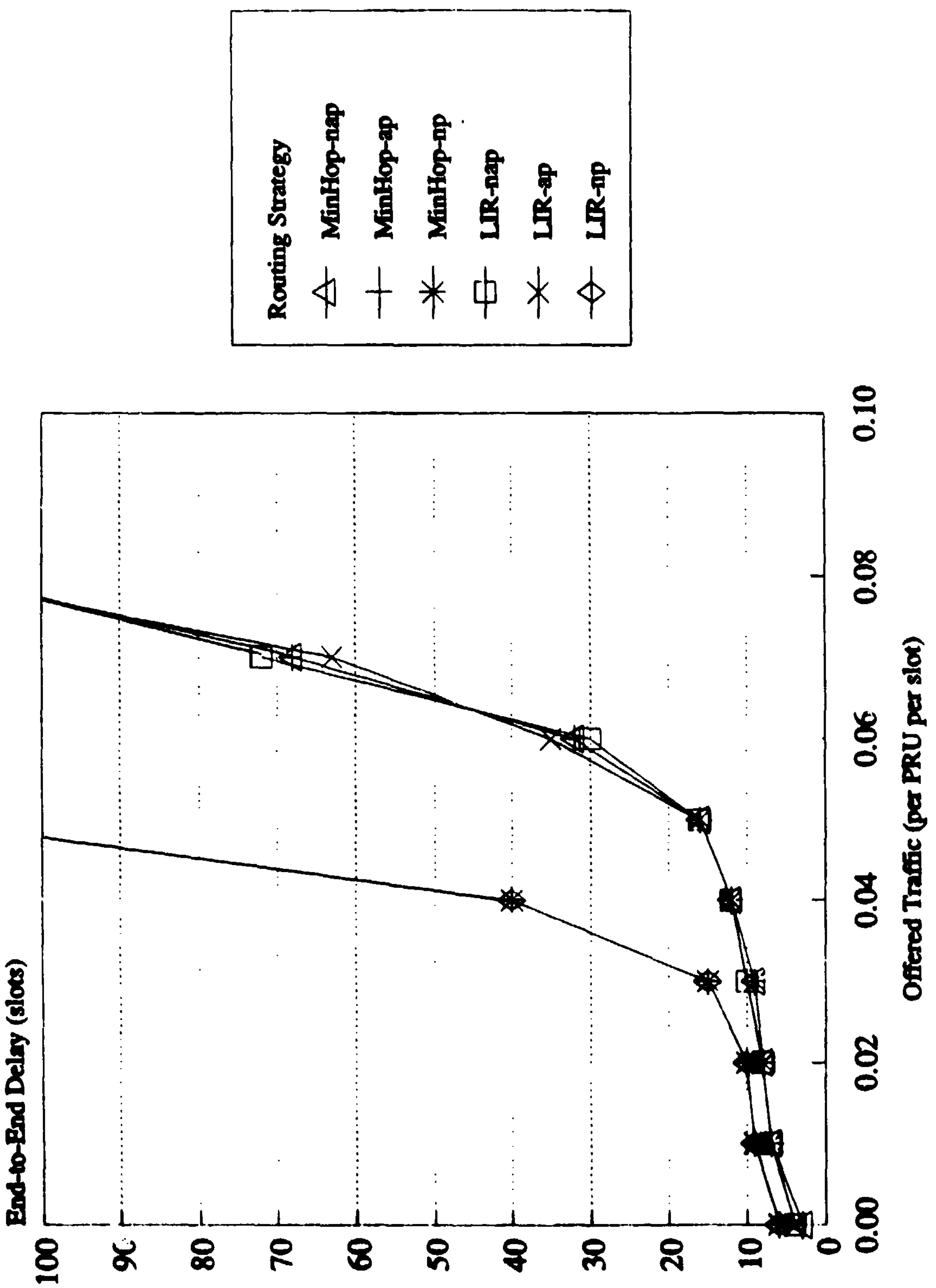


Figure 7-11. End-to-End Delay Versus Offered Traffic

for 10 Node Fully Connected PRNETs

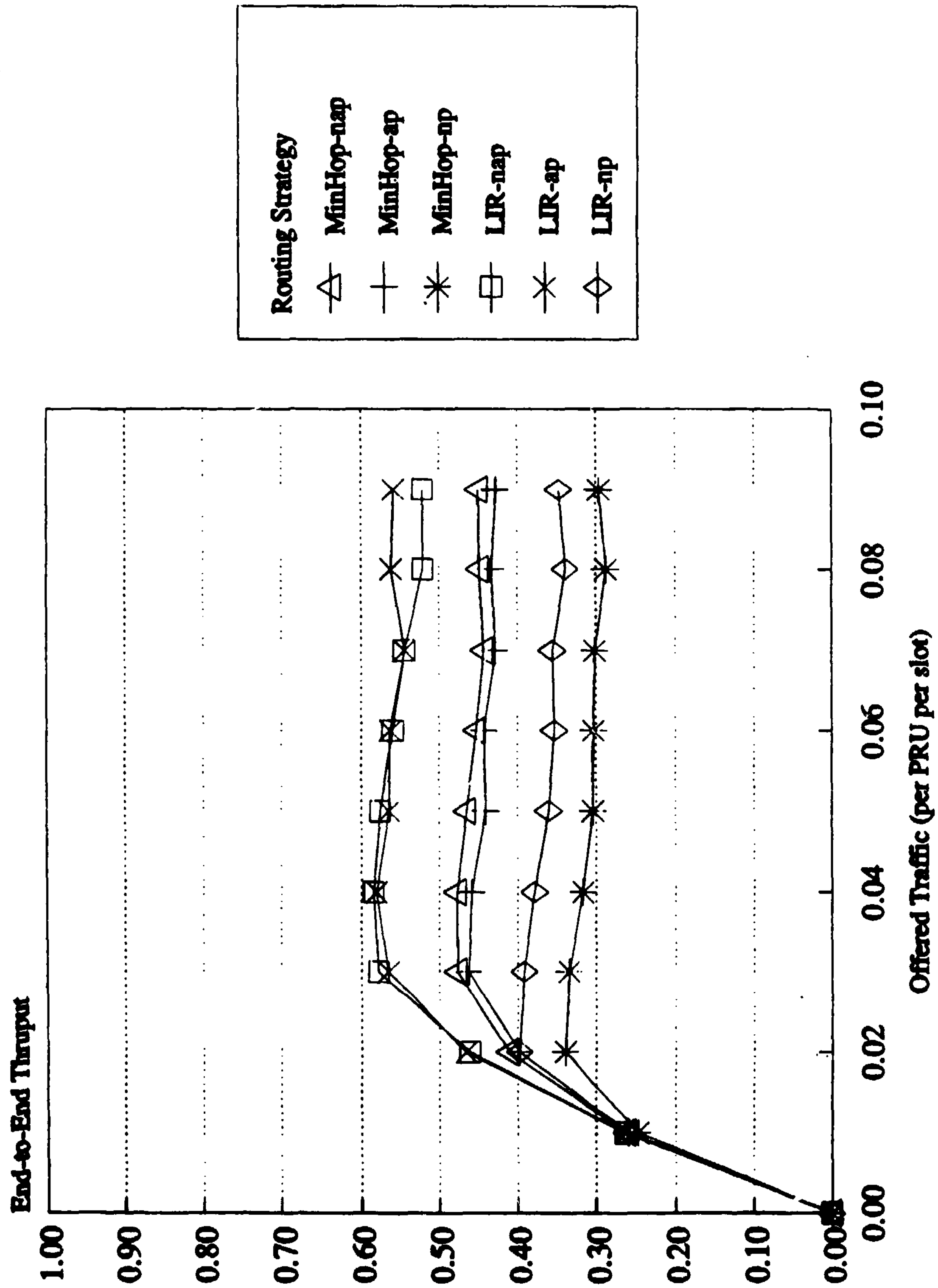


Figure 7-12. Throughput Versus Offered Traffic

for 25 Node PRNETs with Transmit Radius = 25

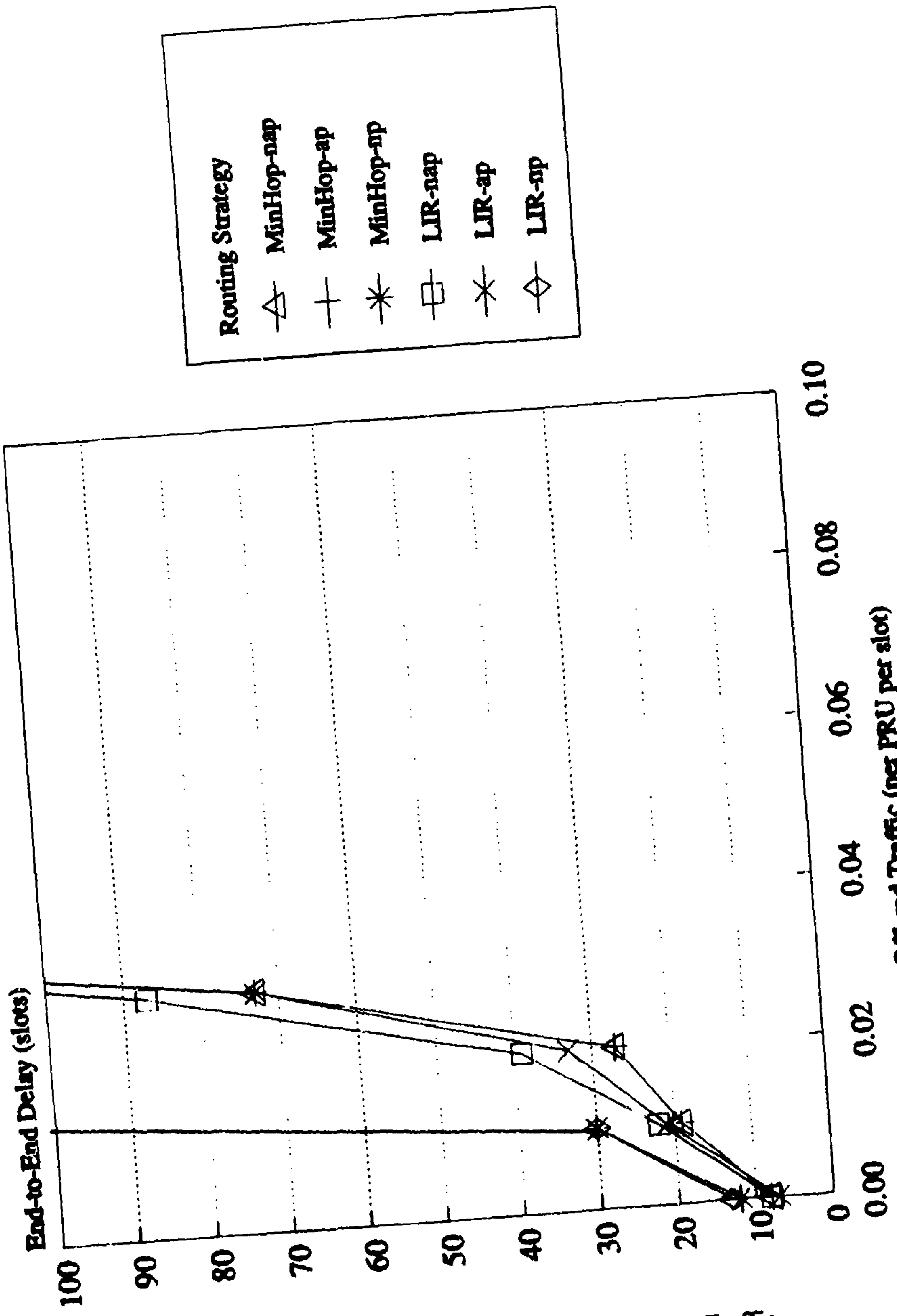


Figure 7-13. End-to-End Delay Versus Offfered Traffic

for 25 Node PRNETs with Transmit Radius = 25

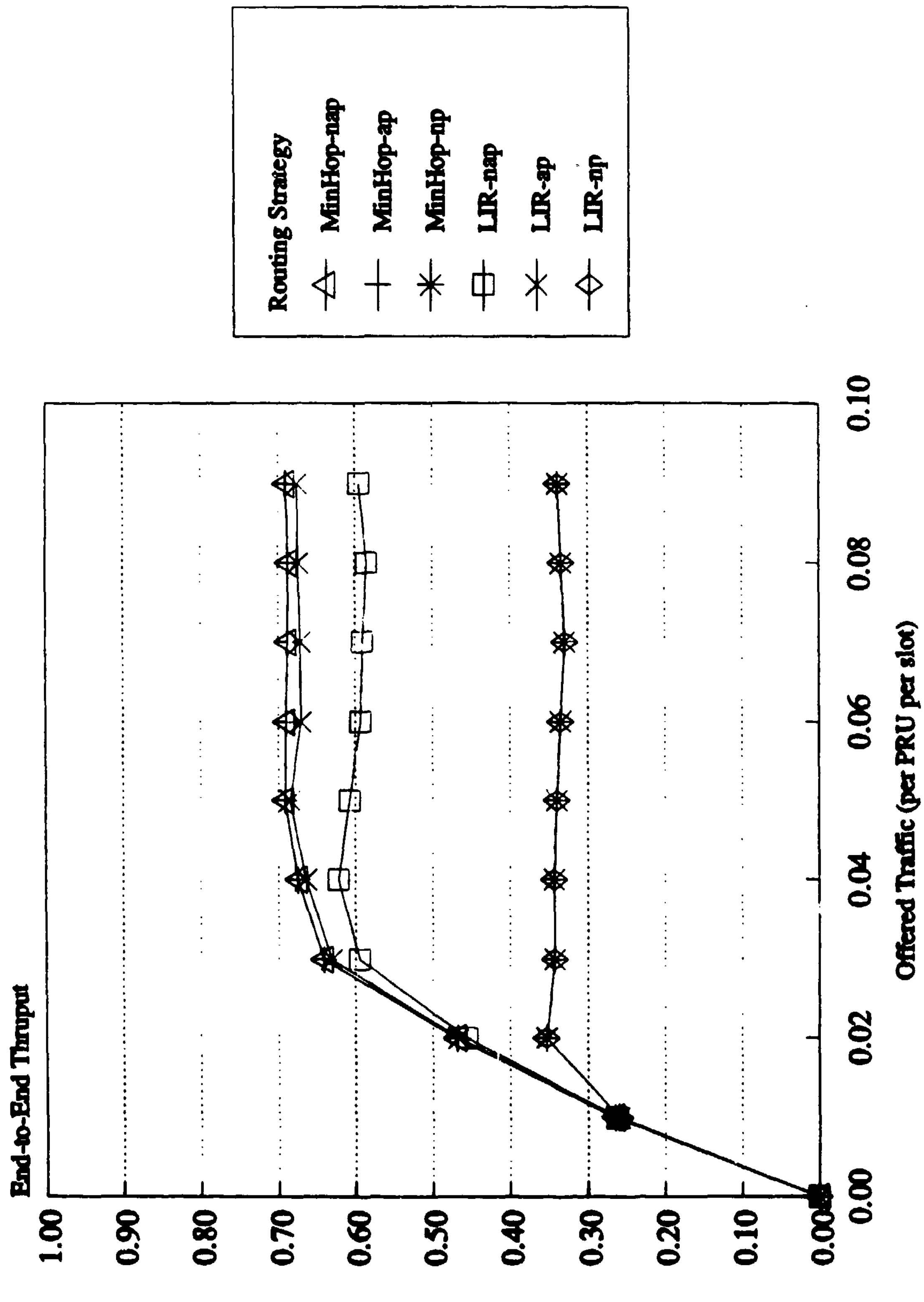


Figure 7-14. Throughput Versus Offered Traffic

for 25 Node Fully Connected PRNETs

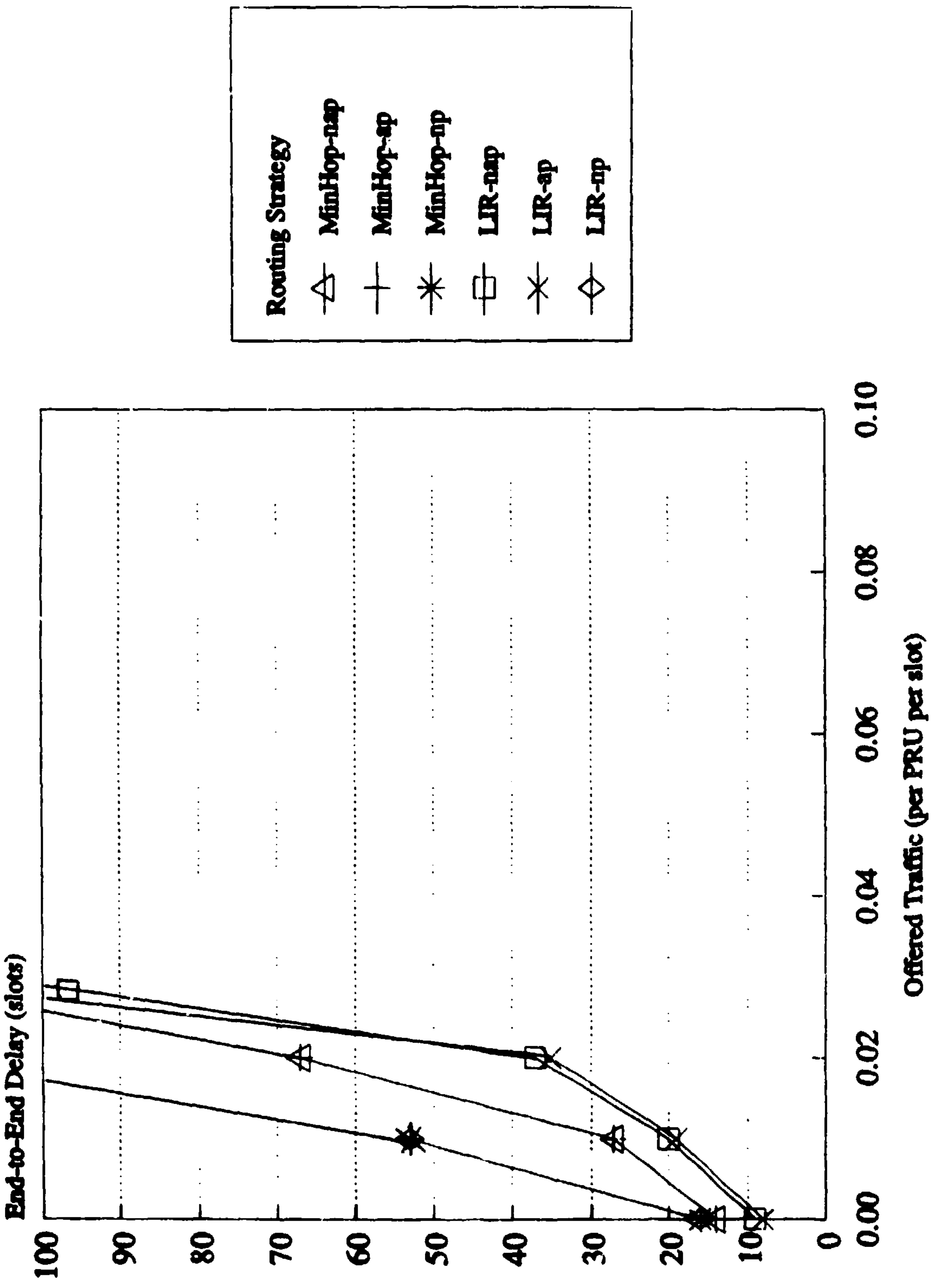


Figure 7-15. End-to-End Delay Versus Offered Traffic

for 25 Node Fully Connected PRNETs

hops per route times the average Aloha transmission interval (or half the maximum Aloha transmission interval), since, in the limit there will be no retransmission or queueing delays.

Figure 7-16 shows the end-to-end throughput versus the number of nodes in the PRNET using a maximum transmission radius of 25 units, i.e., for partially connected PRNETs. We see the following stratification in performance: MinHop-np performs the worst, followed fairly closely by LIR-np, followed by MinHop-nap and MinHop-ap, followed finally with LIR-nap and LIR-ap performing the best. We see that for 25 or more nodes, the PRU performance for LIR with power control is proportional to the logarithm of the number of PRUs in the network. The fairly flat performance of the three MinHop strategies and LIR-np probably arises from the fact that average neighborhood size increased while the maximum transmission radius did not. Therefore, as the number of nodes increases for these four strategies, so does the average interference per transmission.

Next, we examined the performance of partially connected PRNETs, where the average neighborhood size (for a PRU whose transmission range is entirely within the 50-by-50 square) remained constant as the number of PRUs in the PRNET increased. Figure 7-17 shows the throughput versus number of PRUs where the average neighborhood size contains ten PRUs. Figure 7-18 shows the throughput versus the number of PRUs where the average neighborhood size contains 20 PRUs. For an average density of 10 PRUs per neighborhood, we used a maximum transmission range of 28 units for the 10 node PRNET, 18 units for the 25 node PRNET, 13 units for the 50 node PRNET, and 9 units for the 100 node PRNET. For an average density of 20 PRUs per neighborhood, we used a maximum transmission range of 40 units for the 10 node

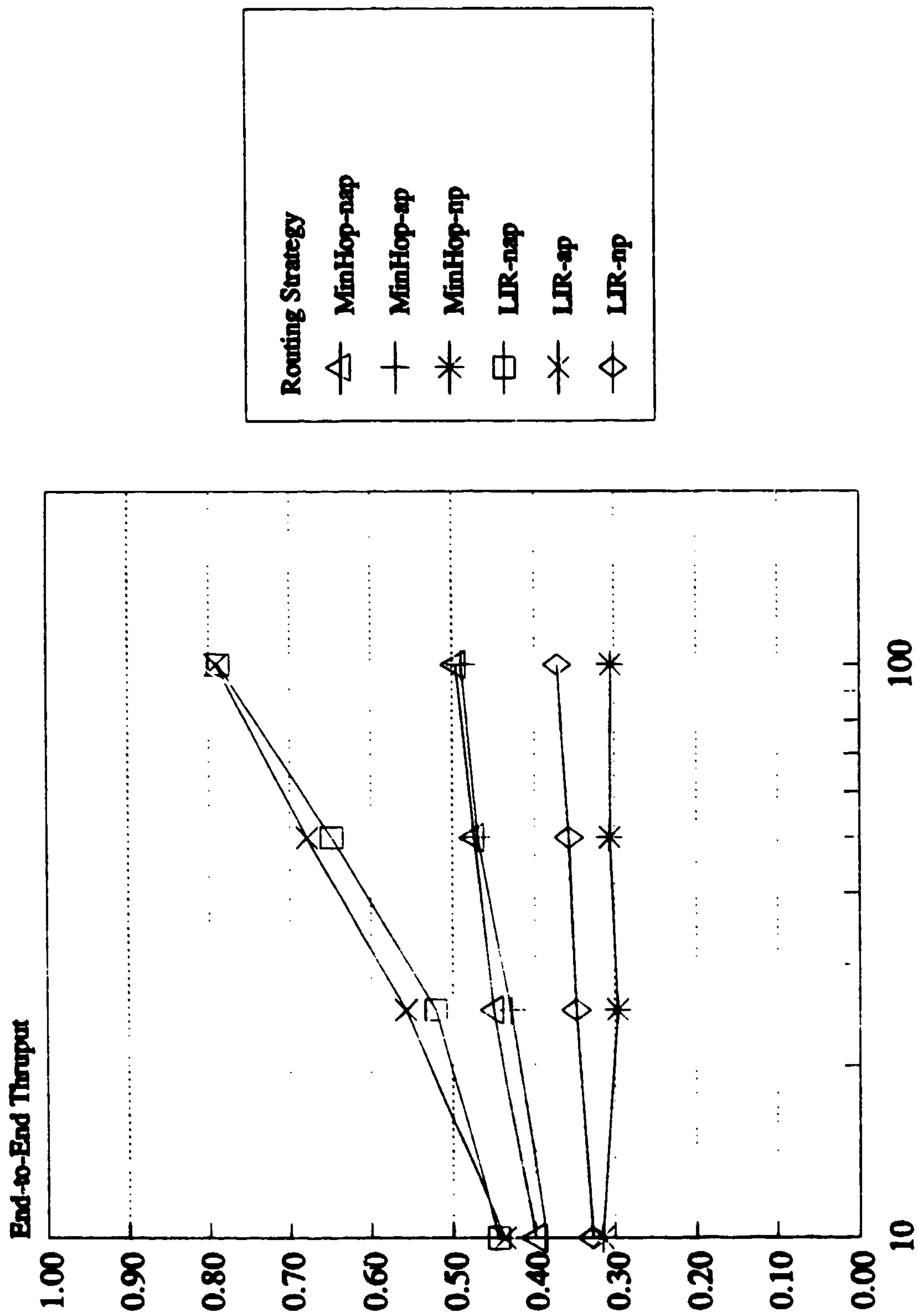


Figure 7-16. Throughput Versus Number of Nodes

for Transmit Radius = 25

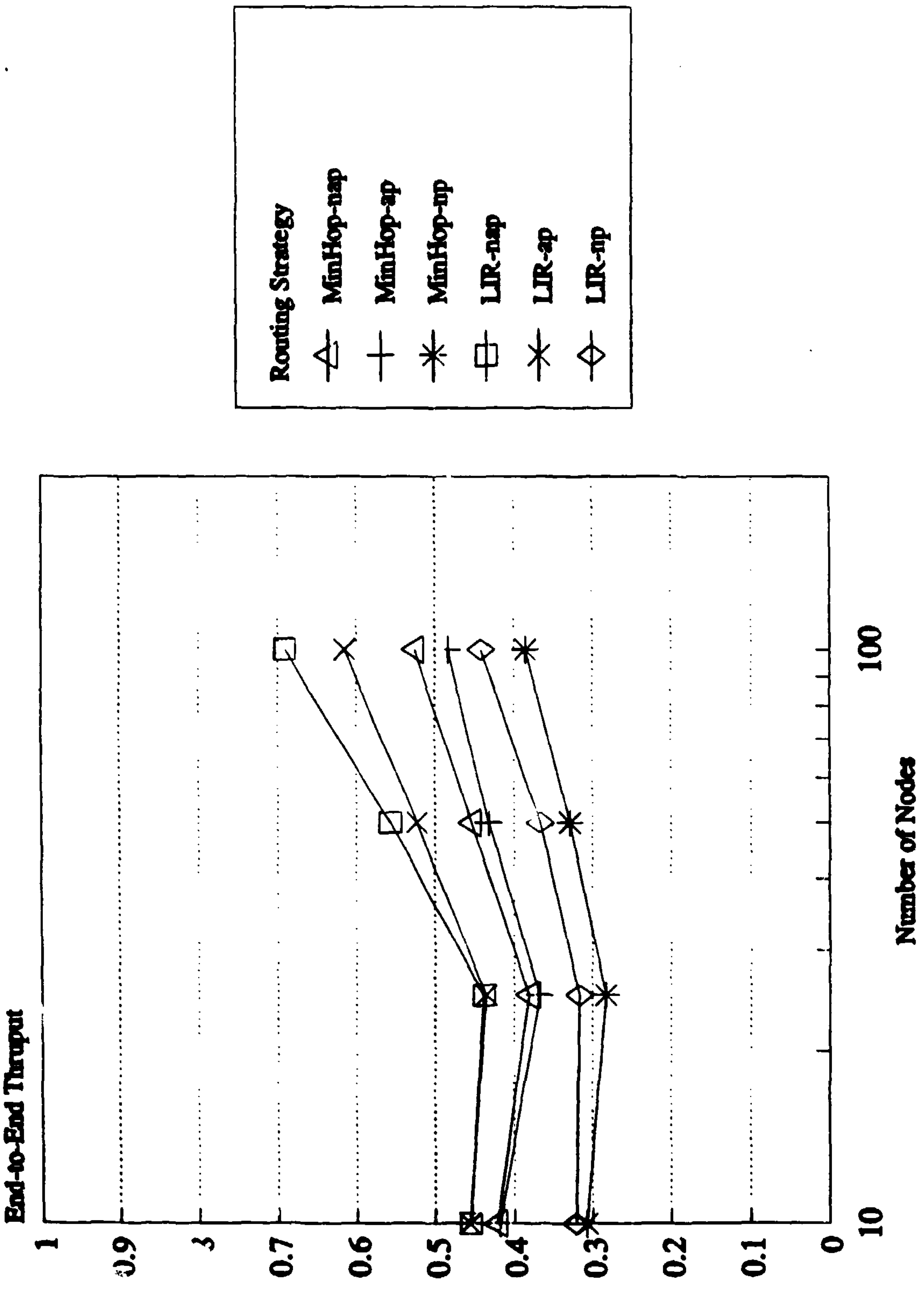


Figure 7-17. Throughput Versus Number of Nodes

for Averge Degree of 10

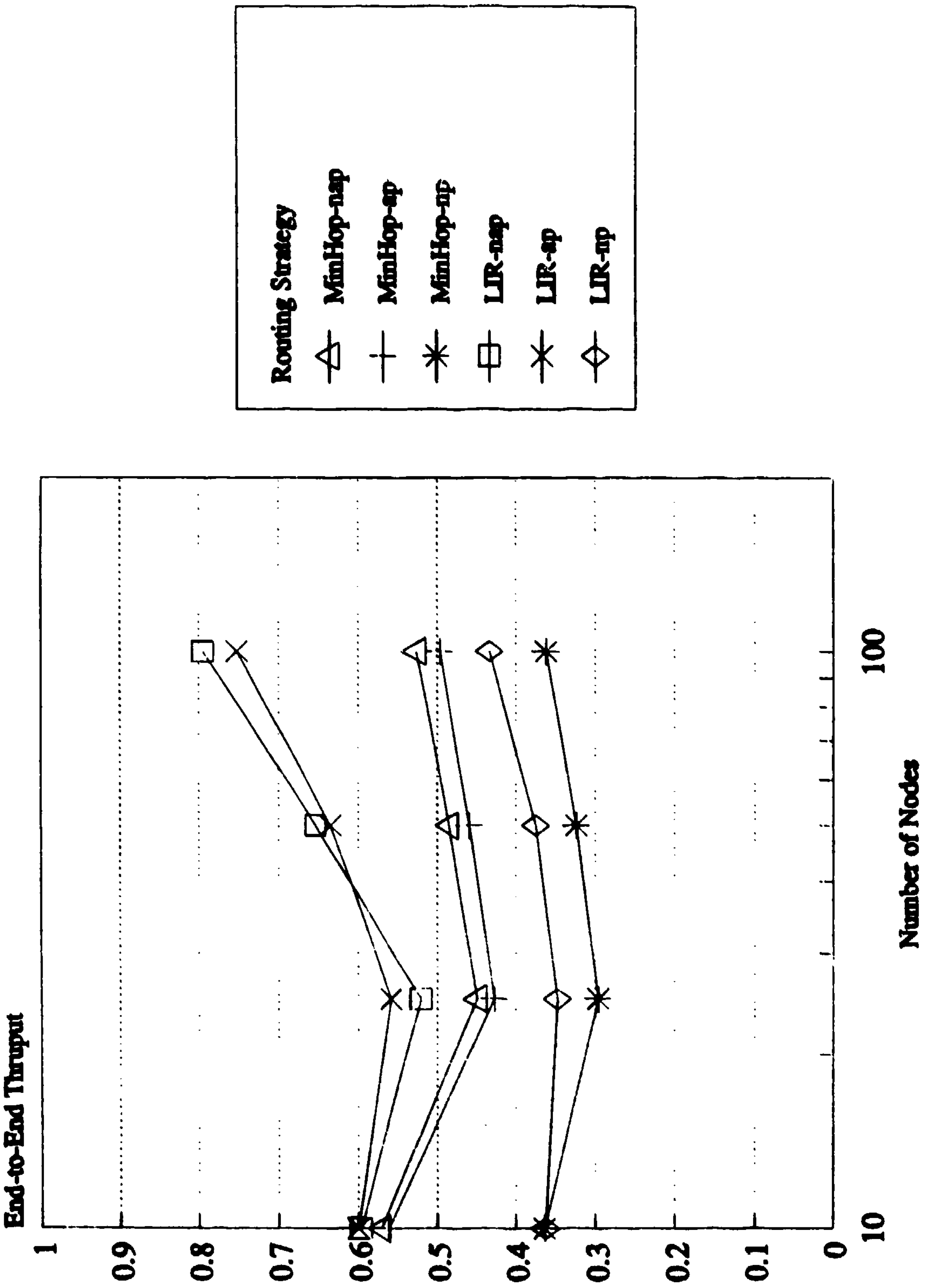


Figure 7-18. Throughput Versus Number of Nodes

for Averge Degree of 20

PRNET, 25 units for the 25 node PRNET, 18 units for the 50 node PRNET, and 13 units for the 100 node PRNET. Figure 7-19 shows the actual and theoretical average neighborhood size to illustrate the importance of edge effects for the different sized networks that were simulated to obtain the results of Figure 7-17. We can see that the edge effects decrease, e.g., the average neighborhood size converges to the expected neighborhood size as the number of PRUs in the PRNET increase. Note that the maximum transmission range for both cases for the 10 node PRNET included area outside of the 50-by-50 square. Some partitioned networks were generated and used when we made the average density equal to 10 PRUs per neighborhood.

The performance increases as the logarithm of the number of PRUs for all six routing strategies when the number of PRUs in the PRNET is greater than 25. The greater than expected performance for the 10 node PRNET, when compared to the other size PRNETs, probably arises due to extreme edge effects on the 10 node PRNET. We notice the same performance stratification among the six routing strategies as before, with LIR with power control performing the best, followed by MinHop with power control, followed by LIR-np, and with MinHop-np performing worst. In general, as expected, the LIR-nap and MinHop-nap performance is better than the respective LIR-ap and MinHop-ap performance.

Figure 7-20 shows the end-to-end throughput versus the number of PRUs for fully connected PRNETs. We noticed that the routing strategies without power control have an end-to-end throughput of about 1/e, while the minimum hop routing strategies with power control have an end-to-end performance of about 2/e. Both of these results agree with the expected theoretical performance of slotted Aloha, thus providing confidence in the correctness of the mul-

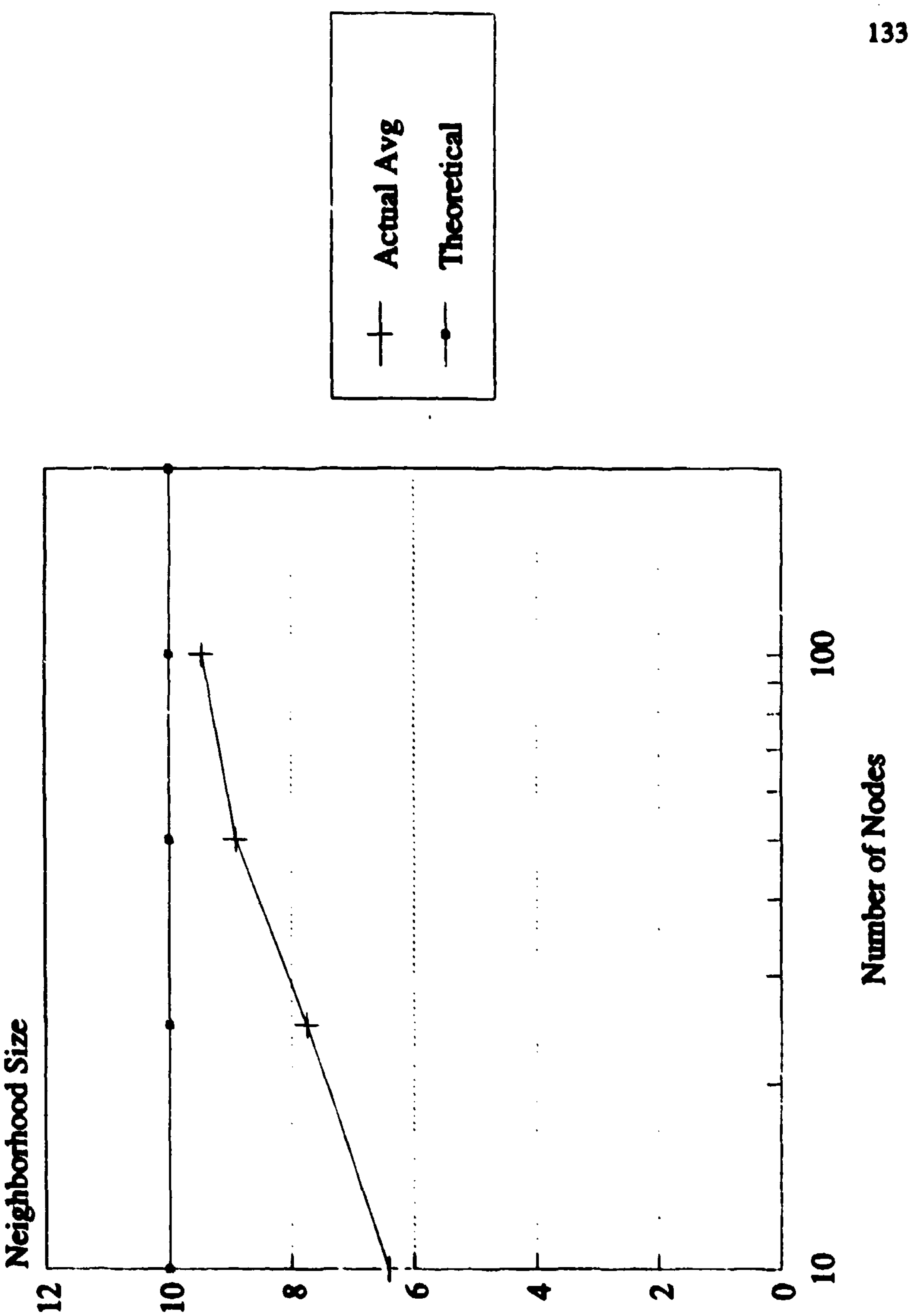


Figure 7-19. Average Neighborhood Size Versus Number of Nodes

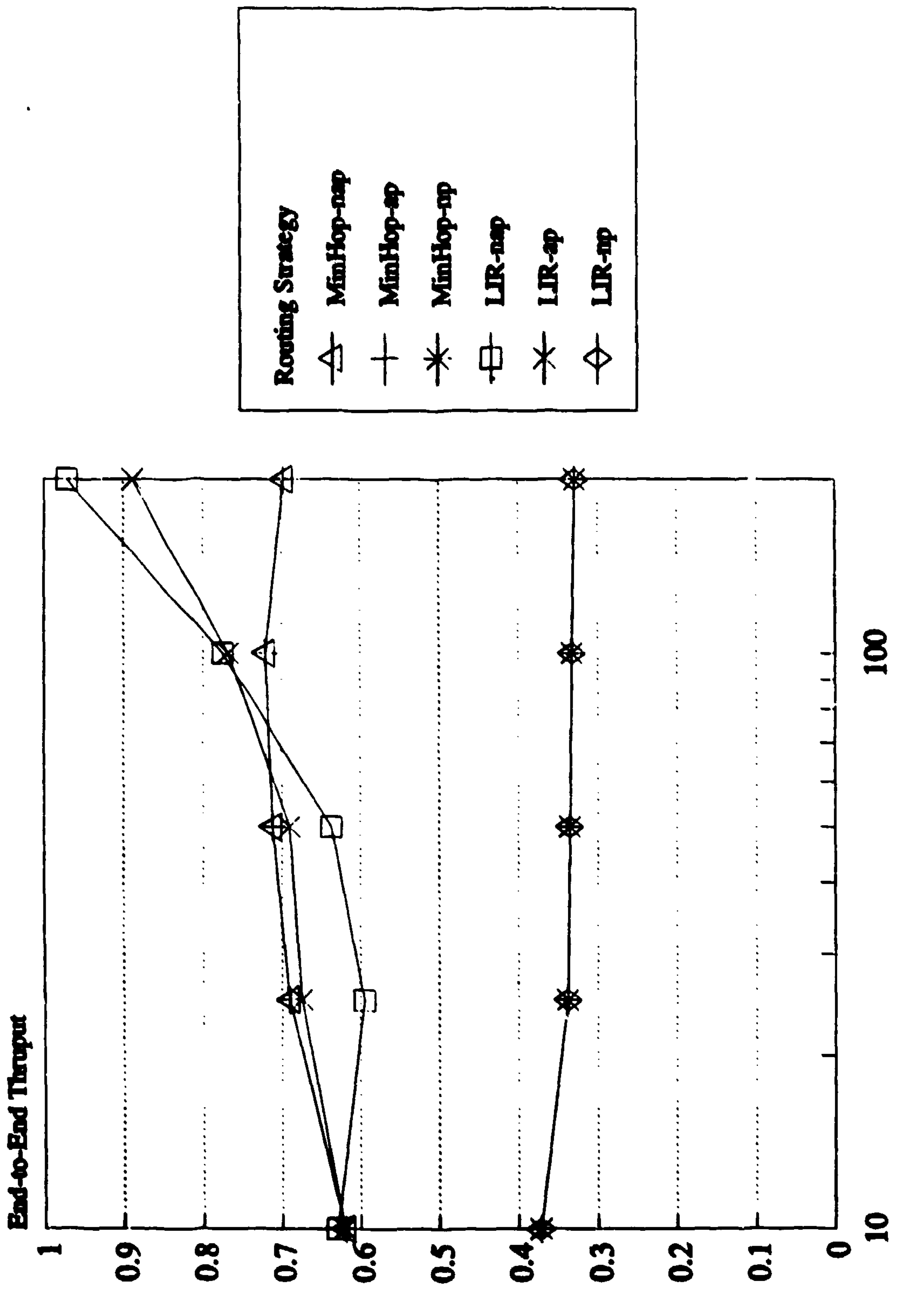


Figure 7-20. Throughput Versus Number of Nodes

for Fully Connected PRNETs

tihop simulation. The slotted Aloha maximum performance of 1/e for a fully connected network without power control is a well-known result proved by Roberts [Rober75]. The slotted Aloha maximum performance of 2/e for a fully connected network with power control is a less well-known result proved by Silvester [Silve80]*

We note that, as expected, LIR-np and MinHop-np perform exactly the same as do MinHop-nap and MinHop-ap for the fully connected PRNETs. MinHop with power control and LIR-ap both have the same performance for 10, 25, and 50 node PRNETs. Also, the LIR-nap performance is lower than MinHop-nap and LIR-ap for 25 and 50 node PRNETs. Throughput for LIR nap and LIR ap increase as the logarithm of the number of PRUs with LIR nap ultimately performing better than LIR ap for PRNETs having 200 or more nodes.

In conclusion, we note that PRNET performance using LIR is greater than or equal to

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* A brief sketch of Silvester's analysis of the slotted Aloha maximum performance for a fully connected network with power control is as follows: Every PRU in the PRNET transmits to every other node with identical probability and adjusts its transmit power to just reach the intended PRU. Therefore, on the average, a PRU will hit n/2 PRUs, which is the average neighborhood size.

Now, the average probability of a successful transmission by a single PRU is:

s = Pr{source PRU transmits on average} x
Pr{destination PRU does not transmit on average} x
Pr{PRUs in average neighborhood around destination do not transmit on average}

Because, we assume that the PRUs are identical, they all transmit with the same probability on average, p. Thus:

$$s = p\,(1 - p)\,(1 - p)^{n/2 - 2}$$

By differentiating with respect to p, we see that the performance is optimized when p = n/2. Thus:

$$s = n/2\,(1 - n/2)^{n/2 - 1} \cong 2(n/e) \text{ for large n}$$

Thus, the total network single hop throughput S, which is also equal to the total end-to-end throughput for a fully connected PRNET, is n s, so that

$$S = n\,s = 2/e \text{ for large n}$$

that using MinHop routing. In addition, LIR-np out performs MinHop-np if the network is only partially connected. This is solely a function of the routing and does not show up in the myopic simulation (see Figures 6-14 through 6-18 where LIR with one power level performs identical to MFR).

8. SUMMARY

8.1 Conclusions

This dissertation has presented methods of performing power control and spatial reuse in operational common-channel random-access PRNETs. Although, the methods presented will work in other types of PRNETs, they have their biggest impact in common-channel random-access PRNETs. These methods are apparently the first to lend themselves to implementation in operational common-channel random-access PRNETs.

Methods of implementing power control were presented that will work below any network routing algorithm. These methods include suggestions on how to work with both passive and active hop-by-hop acknowledgments.

A new routing protocol, Least Interference Routing (LIR), was presented that directly minimizes the total potential PRNET performance degrading interference along a route, thus supporting spatial reuse. LIR will work in PRNETs with and without power control because it routes packets through the sparse parts of the PRNET. LIR is an easy-to-implement algorithm that does not require position location information or rf measurements such as s/n ratios.

Myopic and multiple-hop simulation results indicate that dynamic power control improves network performance over a single constant power level and that LIR improves network performance over Minimum-Hop routing.

8.2 Areas for Future Research

There are many areas of research suggested during the course of this research that are worthy of further study. Some of these areas are:

(1) Implementation of Power Control and LIR

Although the simulations indicate that power control and LIR can be performed in PRNETs to improve performance, it would be useful to implement these algorithms for test purposes in actual operational PRNETs. Indeed it is likely that the DARPA SURAN program will implement the power control algorithms in the latest generation LPR DARPA PRNETs.

(2) Methods of Measuring Potential Destructive Interference

This dissertation suggests some simple methods of measuring the potential destructive interference across a link. We do not include the different effects from the overlap function caused by different channel access protocols, i.e., CSMA. This would be a useful area for further research because many operational PRNETs use CSMA.

Many advanced PRNETs use spread spectrum which alleviates but does not eliminate interference. Therefore, it would be useful to obtain some methods of measuring the potential destructive interference in operational spread spectrum PRNETs.

(3) Methods of Reducing Route Bottlenecks at PRUs

LIR is similar to any shortest path routing algorithm in that it assumes that each route is fairly independent of other routes. Therefore, it is possible that many routes can go through one PRU, causing a bottleneck. Although LIR does help spread routes from the middle of networks to the outside, it does not explicitly take the bottleneck problem into consideration. Ogier is currently examining this problem as part of the DARPA SURAN program [Ogier87].

(4) Methods of Including the Offered Traffic

LIR is designed for the uniform offered traffic case. Greater spatial reuse may be realized if the actual traffic were taken into consideration. Ogier is currently examining how to include power control with traffic-dependent routing as part of the DARPA SURAN program [Ogier87].

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APPENDIX A. ACRONYMS

AM	amplitude modulation
ANSI	American National Standards Institute
ARPANET	Advanced Research Projects Agency Network
ARQ	automatic-repeat-request
BLOS	beyond-line-of-sight
BTMA	busy tone multiple access
CDMA	code division multiple access
CNR	combat net radio
CSMA	carrier sense multiple access
DARPA	Defense Advanced Research Projects Agency
dB	decibel
dBm	power in dB above 1 milliwatt
DoD	Department of Defense
ES	End System
EW	electronic warfare
FDMA	frequency division multiple access
FEC	forward-error-correction
FH	frequency hopping
FIFO	first-in, first-out
FM	frequency modulation
GHz	Giga Hertz
GPS	Global Positional Satellite
hf	high-frequency
HICAPCOM	High Capacity Communications
IS	Intermediate System
ISO	International Standards Organization
LAR	Least Area Routing
LIR	Least Interference Routing

LIR-ap	LIR with acknowledgments and power control
LIR-nap	LIR without acknowledgments but with power control
LIR-np	LIR without power control
LOS	line-of-sight
LPR	low-cost packet radio
MFR	Most forward with Fixed Radius
MHz	Mega Hertz
MinHop	Minimum-Hop routing
MinHop-ap	Minimum-Hop routing with acknowledgments and power control
MinHop-nap	Minimum-Hop routing without acknowledgments but with power control
MinHop-np	Minimum-Hop routing without power control
MSS	Multiple Satellite System
MVR	Most forward with Variable Radius
NFP	Nearest with Forward Progress
OSI	Open Systems Interconnection
PN	pseudo-noise
PRNET	packet radio network
PRU	packet radio unit
rf	radio frequency
RSRE	Royal Signals and Radar Establishment
SCRA	Single Channel Radio Access
SEEP	Simple End-to-End Protocol
SEFN	Survivable Extended Frequency HF Network
SINCGARS	Single Channel Ground and Airborne Radio System
s/n	signal-to-noise
SURAN	Survivable Adaptive Networks
TDMA	time division multiple access
uhf	ultra-high-frequency
vhf	very-high-frequency

APPENDIX B. SYMBOLS

A	area
d	average degree,i.e. average number of neighbors
I(i)	amount of potential PRNET performance degrading interference caused by a PRU-i transmission
I(i,k)	amount of potential performance degrading interference a PRU-i transmission causes to otherwise successful receptions by PRU-k
I(i,j,k)	conditional probability that a PRU-i transmission causes destructive interference with an otherwise successful transmission from PRU-j to PRU-k, given that the PRU-i and PRU-j rf signals overlap in time at PRU-k
L	forward progress
M	number of PRUs which can hear a transmission
O(i,j,k)	probability that the rf signals transmitted by PRU-i and PRU-j overlap in time at PRU-k
p	transmission probability
Pr{ }	probability function
R	distance between transmitter and receiver
R*	actual transmission range
R'	minimum transmission range
R"	maximum transmission range
Rp(i)	transmission range at power level i
s	single node single hop throughput
S	network single hop throughput
z	single node expected forward progress
Z	network expected forward progress
λ	average density of nodes per unit area
π	pi (3.14159 ...)

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